THE UNIVERSITY OF ALBERTA

"ANALYSIS BY SPATIAL FILTERING OF SOME INTERMEDIATE SCALE STRUCTURES IN SOUTHERN ALBERTA"

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Analysis by Spatial Filtering of some Intermediate Scale Structures in Southern Alberta", submitted by Joseph Edward Robinson, B. Eng., M. Sc., in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

Five structural contour maps of the interior plains of southern Alberta were compiled from exploratory well elevations. The maps expressed a combination of structures with a wide variation in relief and spacing. As only the intermediate scale structures were to be analysed, spatial filtering was used to suppress conflicting structures that were outside of the desired size range.

Harmonic analysis allows each structure to be expressed in terms of a limited band of sinusoidal surfaces of specific amplitude, wavelength and phase. Spatial filtering suppresses undesired structures by deleting their wavelengths and retaining the wavelengths of the desired structures. The process requires a high speed digital computer and involves determining the wavelengths present, designing a spatial filter to remove the undesired wavelengths and filtering the map.

The maps and their amplitude spectra were analyzed to determine the maximum range of desirable wavelengths and several filters were designed to enhance different portions of this range. The filters were designed in the frequency domain and their spatial equivalents determined by means of two-dimensional Fourier transforms. The maps were digitized on a two mile interval and the spatial filters convolved with a test

area to determine the best filter for southern Alberta. Finally the optimum filter was used to produce a new suite of filtered structural contour and apostreptic maps displaying the desired structures.

A structural analysis indicates the presence of two dominant intermediate scale structural trends that are aligned either NE-SW or NW-SE similar to those of the Precambrian Churchill province of the Canadian shield. The trends are present in all maps but with diminished relief on the upper surfaces. The structures appear to be essentially tabular bodies caused by minor vertical adjustments along planes of weakness originating in the Precambrian basement.

The analysis also suggests the presence of a NW-SE trending wrench fault in the Edmonton area that was active just prior to the time of Cretaceous deposition. Finally, southern Alberta can be roughly divided into three large structural domains approximately equivalent to known basement divisions. The structural trends highlighted by the filtering process are coincident with many of the known oil and gas fields and tectonic movements may have exerted a pronounced influence on hydrocarbon entrapment.

ACKNOWLEDGEMENTS

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Mr. R.C. Hyslop, of Imperial Oil Ltd., first pointed out to the writer the orthogonal structural trends from seismic data. Dr. J.E. Hogg and Mr. E.K. Shaw suggested that filter theory would be useful in geological interpretation.

Imperial Oil Limited supplied the original well information. Financial assistance was received from a Hudson's Bay Oil and Gas Company Limited Fellowship, a Graduate Teaching Assistantship from the University of Alberta, and through research grants originating from the National Research Council

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TABLE OF CONTENTS

Page

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION

The Interior Plains of southern Alberta are generally of low relief and covered by till, so that outcrops of bedrock are scarce and are confined to river valleys and the slopes of outliers such as the Cypress Hills. The low relief and the flat or gently inclined nature of the immediately underlying sediments permit little of the three dimensional structure in the sedimentary column underlying the Interior Plains to be determined from a study of the outcrops.

The structure of a rock body is described by the nature and orientation of the contained, identifiable surfaces and lines. These surfaces and lines, irrespective of their origin, are called structures. A structural analysis, whether of a single fold or of a large area, is limited by the available information. Direct measurements on well exposed features are best, but in areas such as the Interior Plains where exposures are scarce, a great deal of information can be obtained from bore holes or indirect geophysical measurements. In the case of bore holes or wells where the spacing cannot be readily controlled, the scale of structures that may be included in the analysis is directly related to the number and spacing of the available sample locations. It can be shown that a structural analysis of intermediate scale structures, those with a minimum dimension between ten and fifty miles, either requires good outcrop exposure or bore holes with an average spacing of

not more than five miles.

The outcrops of Upper Cretaceous and Lower Tertiary rocks in the Interior Plains have enabled depositional environments to be established. However, the near surface beds are almost flat lying with only occasional local exposures of glacial and tectonic structures so that surface geology permits only a surficial picture of the tectonic history of the Interior Plains of southern Alberta. Analysis in depth must rely to a large extent on subsurface sources of information.

Fortunately, the sedimentary rocks of the Interior Plains are a prolific source of hydrocarbons. Between the first commercial discovery in 1883 and the summer of 1966, some 15,000 wells were drilled within the thesis area of which approximately 7,500 were exploratory ventures for the purpose of locating new oil and gas fields. Exploratory wells are ideal for a structural study, for not only have they been thoroughly examined by the drilling companies, but also, due to the vagaries of exploration methods, their locations approximate a statistically random distribution.

Exploratory wells are extensively sampled, prospective horizons are cored, and the entire well is usually surveyed with a variety of wire-line logs so that 7,500 wells represent a very large amount of geological information. Consequently, most regional studies (see e.g. McCrossan and Glaister, 1964)

have used only representative samples of the available wells and thus have been restricted to the analysis of the large-scale structures and to descriptions of the regional stratigraphy. Local small-scale structures deduced from surface geology and development wells have also been described (see e.g. Russell and Landes, 1940), but it is only quite recently that the exploratory wells have reached a sufficient number and concentration to permit analysis of the intermediate-scale structures. Since their delineation requires the examination of very large numbers of sample values, the necessary analytical procedures are most effective when carried out on high speed digital computers.

Digital computers are well suited to handling large amounts of geological data as long as it is in suitable form. They can relieve the geologist of most of the tedious and error generating mathematical operations. Since computer methods are largely mechanical and must conform to mathematical logic, their use opens the door to procedures that are not normally associated with structural analysis. If the geological information describing a structural surface can be digitized on a uniform interval, then filter theory can be used to design operations that will facilitate the analysis. It can, in fact, be separated into two parts, an analytical part that is mathematically rigorous, and a descriptive part that is based on previous geological experience and intuition.

This thesis documents an attempt to design and apply computer-oriented techniques to an analysis of the intermediate scale structures of the Interior Plains of southern Alberta. The structures are examined with respect to the overall tectonic patterns and within the limits of the available information, their origin and possible economic significance are suggested.

Project Area

The area of study (Figure 1) consists of the Interior Plains of southern Alberta south of the 55th parallel. It has an areal extent of some 100,000 square miles, contains approximately 160,000 cubic miles of sedimentary rock and is entirely within the Western Canadian Sedimentary Basin.

Previous Work

The first geological survey within the thesis area was undertaken by Sir James Hector, physician and geologist with the Palliser expedition of 1857 to 1860. The next was by G.M. Dawson who examined the geology in the vicinity of the 49th parallel in 1874 and, accompanied by R.G. McConnell spent the summer of 1881 mapping as far north as the Red Deer river. Together and separately, Dawson and McConnell (1885) covered most of what is now southern Alberta.

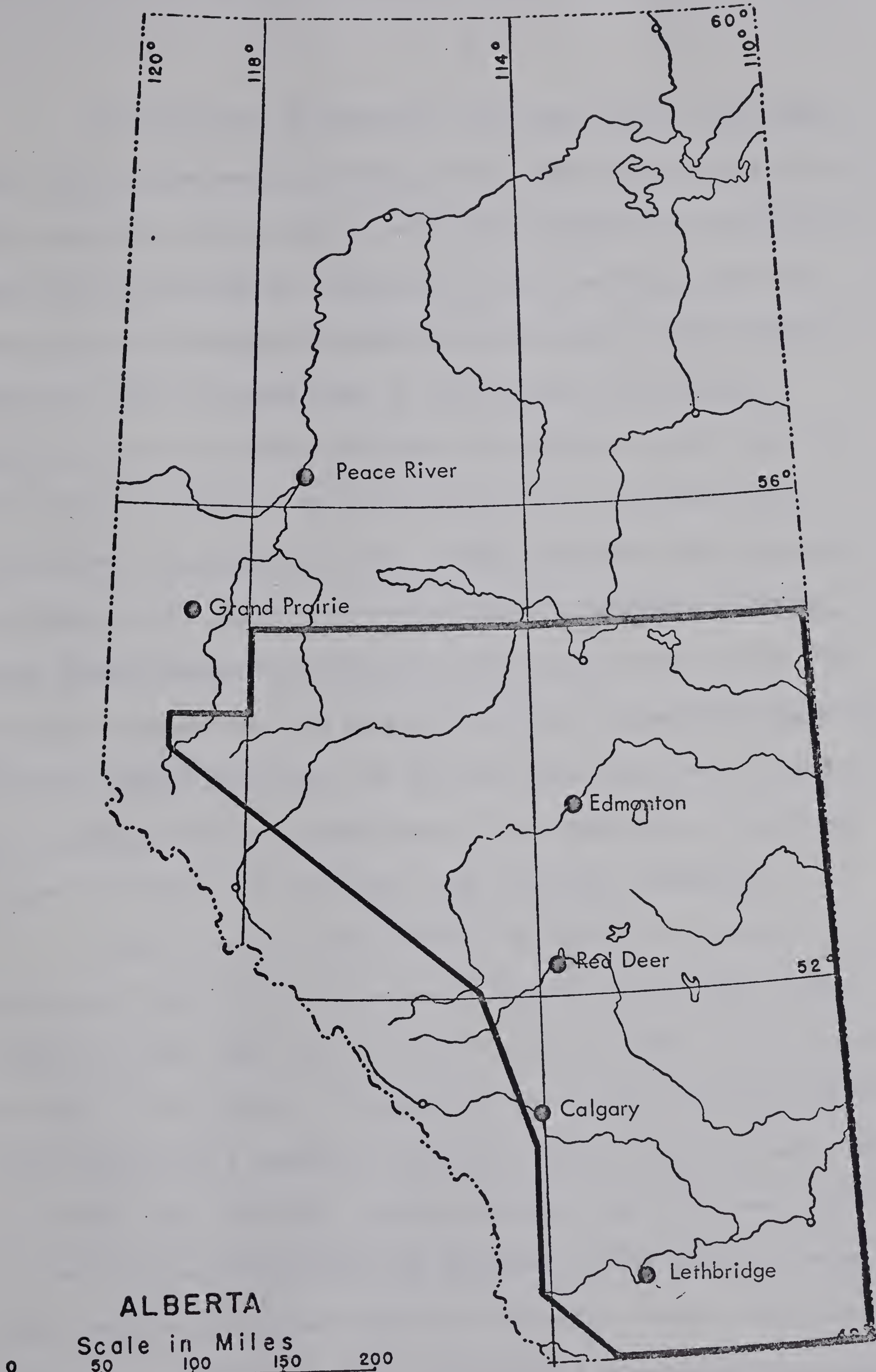

Figure 1. Index map of thesis area

Exploitation of Alberta's coal and natural gas began late in the nineteenth century and oil was discovered early in the twentieth stimulating a continued interest in the detailed geology of the interior plains. The mine workings and well-borings gave geologists access to previously covered strata. Dowling (1917) revised some of the earlier stratigraphic nomenclature and (1919) published structural contour maps on Cretaceous horizons that displayed most of the large-scale structures. Williams and Dyer (1930) described the regional, and many of the small-scale structures of southern Alberta. Hume (1933) showed that structure was significant in the formation of many of the oil pools of central and southern Alberta. Russell (1932) described the Monarch fault near Lethbridge and with Landes (1940) reviewed most of the remaining areas where there is evidence of at least local tectonic movements.

More recently, Webb (1954) outlined the regional structural history of the western Canadian plains and Borden (1956) did the same for the major tectonic trends in the southern part of the basin. The Alberta Society of Petroleum Geologists sponsored a symposium (deMille, Lavoie and Williams, 1958) that dealt with tectonic trends affecting the north-west portion of the area and (McCrossan and Glaister, 1964) edited a remarkably complete geological history of western Canada that gives a detailed description of the large-scale structural and stratigraphic variations.

Sikabonyi (1957, 1959) proposed tectonic patterns that extend across the northern part of the area and Haites (1960) suggested there may be a network of transcurrent faults extending throughout Western Canada. Burwash (1965) outlined the general structural trends present in the Precambrian basement.

Stratigraphic Nomenclature

Stratigraphic nomenclature follows the recommendations of the Alberta Society of Petroleum Geologists (A.S.P.G., 1960; McCrossan and Glaister, 1964) and that of the Oil and Gas Conservation Board of Alberta (1966). A table of formations is given in Figure 2.

Structural Surfaces

A descriptive knowledge of the attitudes of surfaces that would undergo deformation by any tectonic movement is essential to a structural analysis. Structural surfaces for southern Alberta were obtained by using all available exploratory well information to construct structural contour maps on specific stratigraphic surfaces that continuously underlie the

TABLE OF FORMATIONS

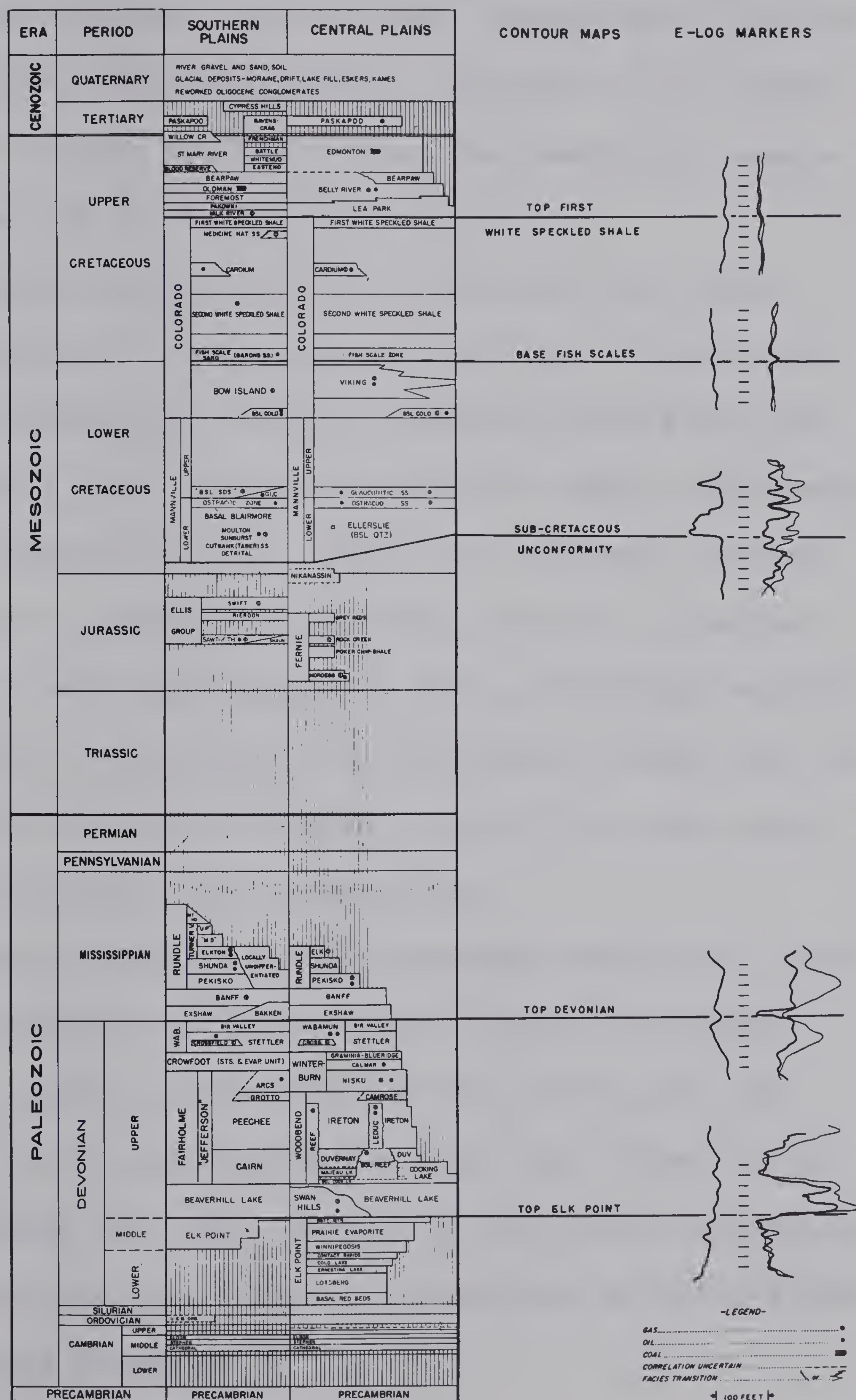

Figure 2

Table of formations for the Interior Plains of Southern Alberta, after the Oil and Gas Conservation Board, 1966.

entire area and can be correlated by standard subsurface methods. The most suitable surfaces for structural mapping are those that closely approximate time stratigraphic surfaces and are spaced throughout the vertical section so that they adequately sample all possible periods of tectonic disturbance.

Structural surfaces used in the analysis are usually a compromise between the ideal and the practical. Elevations of subsurface horizons are normally determined from wire-line logs. Early wells were surveyed only with the basic spontaneous potential and resistivity logs. Thus, for universal coverage, the surface must be an easily discernable electric log marker. Since there is a very large number of wells, structural surfaces must correspond to very distinctive lithological breaks that can be readily identified and correlated by any of the many geologists who do the actual log interpretation.

The cost of drilling a well increases rapidly with depth and there is attenuation of well control towards the deeper horizons. The balance between the cost of drilling and the prospects for oil and gas discoveries means that there will be one horizon marking the lower boundary of sufficient information for a structural analysis. There is, therefore, a definite depth limit to effective analysis.

Exploratory well information was obtained for four horizons that seemed to meet the requirements of continuity, adequate control, stratigraphic separation and a reasonable approximation to a time stratigraphic surface. Elevations were plotted at the well locations and structural contour maps prepared for use in the analysis. A fifth map on a deeper horizon was also prepared. However, as only a relatively few wells had penetrated to this depth the last map served mainly to show the continuity of the larger structures and the loss in detail inherent in poorly sampled data.

First White Speckled Shale

The uppermost structural contour map, top First White Specks (Figure 3), was prepared on the top of the First White Speckled Shale which is the stratigraphically highest of the depositional surfaces considered suitable for a structural analysis of southern Alberta. This unit marks the top of the Upper Cretaceous Colorado Group and has long been used by the oil industry as a widespread marker horizon (A.S.P.G. 1960). It continuously underlies all but the extreme northwest corner of the area. The main unit generally ranges in thickness from 160 to 190 feet and consists of a grey marine bentonic shale containing lenticular particles of chalk up to half a millimeter in diameter. Immediately north of the Cypress Hills, it

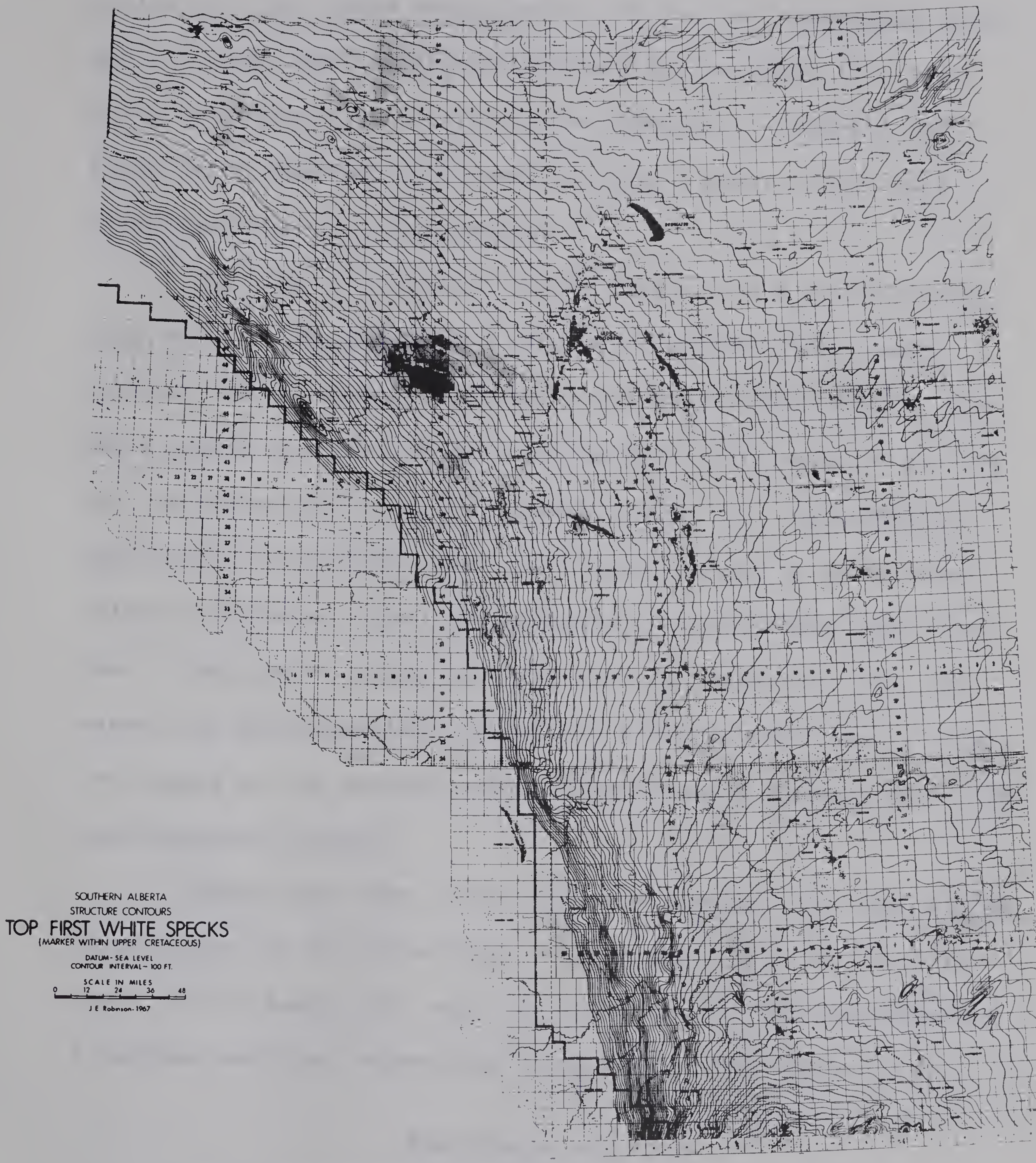
SOUTHERN ALBERTA
STRUCTURE CONTOURS
TOP FIRST WHITE SPECKS
(MARKER WITHIN UPPER CRETACEOUS)
DATUM - SEA LEVEL
CONTOUR INTERVAL - 100 FT.
SCALE IN MILES
0 12 24 36 48
J E Robinson - 1967

Figure 3

splits into two parts separated by 145 feet of unspeckled shale and in other local areas the speckled shales grade into overlying sandstones of the Milk River Formation, However, the First White Speckled Shale normally has a sharp conact with unspeckled shales and sandstones.

The top of the First White Speckles is a suitable mapping surface because it is a widespread depositional marker horizon that is normally picked in all exploratory wells. The white specks are easily identifiable in cutting samples and the unit is a good electric log marker (Figure 2). The standard deviation of the picks under conditions similar to those described by Hitchon (1964) is estimated to be not more than five feet. The upward change from speckled to unspeckled rock represents an environmental change that occurred over much of Western Canada so the surface probably corresponds closely to a time-stratigraphic horizon.

Elevations from 7,422 exploratory wells were used in the construction of the structural contour map. This is the equivalent of one sample for each 13.5 square miles and approximates a uniform sampling interval of root 13.5 or 3.7 miles.

Fish Scale Sandstone

The second structural contour map, the base Fish Scales (Figure 4), was prepared on the base of the Fish Scale Sandstone.

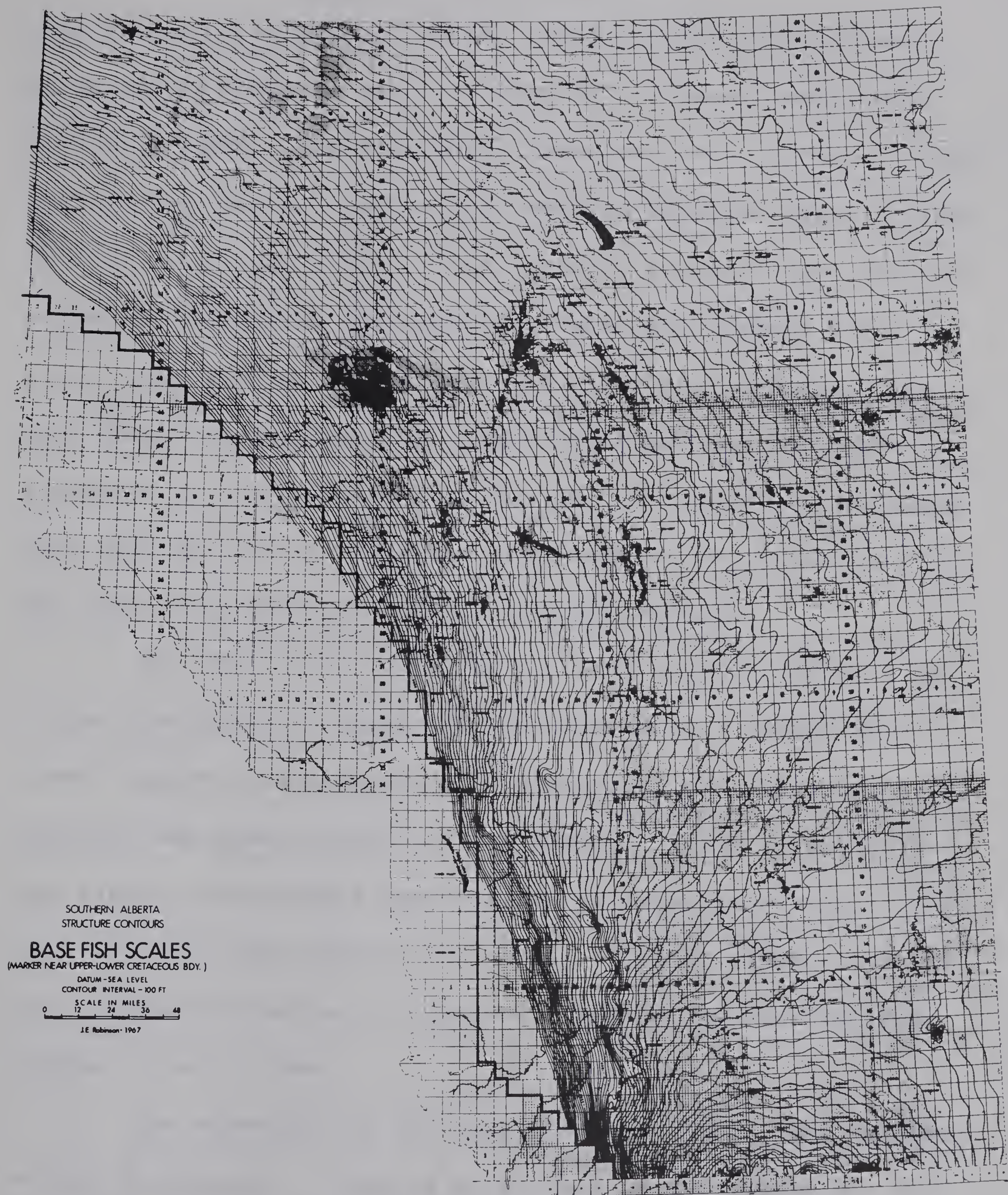
SOUTHERN ALBERTA
STRUCTURE CONTOURS
BASE FISH SCALES
(MARKER NEAR UPPER-LOWER CRETACEOUS BDY.)
DATUM - SEA LEVEL
CONTOUR INTERVAL - 100 FT
SCALE IN MILES
0 12 24 36 48
J.E. Robinson · 1967

Figure 4

This unit is a widespread marker horizon within the Colorado Group and is taken to mark the base of the Upper Cretaceous (A.S.P.G. 1960). The Fish Scale Sandstone is continuous across most of the southern half of the Western Canadian Basin including the entire map area. It is a poorly sorted, light colored sandstone containing the remains of what are assumed to be fossil fish scales. The surface is taken at the base of the unit where the sandstone is better developed and there are an abundance of recognizable fish scales. The sandstone averages less than 30 feet in thickness and forms an abrupt change from the underlying dark grey marine Colorado shales.

The base of the Fish Scales meets the requirements of a time stratigraphic marker for it represents a change from normal marine conditions to ones associated with widespread deposition and preservation of fish scales. It is a distinctive and easily correlatable marker since it causes a strong kick on both electric and radioactivity logs. Hitchon (1964) computed the standard deviation of electric log picks on the base Fish Scales to be 0.5 feet.

The elevation of the base Fish Scales has been determined for 6,933 wells. This is an average of one sample for each 14.4 square miles and approximates a uniform sampling interval of 3.9 miles.

Sub-Cretaceous Unconformity

The basal Cretaceous rocks in western Canada unconformably overlie strata ranging in age from Jurassic in the southwest to Devonian in the northeast. The angular discordance is small but the depositional and erosional vacuity represents a major hiatus. In southern Alberta the Lower Cretaceous basal Mannville sands and conglomerates overlie shales and limestones of the pre-Cretaceous section and form a distinctive marker horizon that can be easily correlated over the entire area. The surface reflects erosional features and the time of non-deposition persisted longer in the eastern part of the area than it did in the west (McCrossan and Glaister, 1964). However, the unconformity is a significant marker and was mapped for use in the structural analysis (Figure 5).

The oil potential of the basal Cretaceous sands and the immediately underlying Jurassic, Mississippian or Devonian rocks has resulted in a large number of exploratory wells that intersect the sub-Cretaceous unconformity. Although it is not the most desirable structural surface, it is the deepest horizon where there is a relatively large amount of well control with a random distribution over the whole of southern Alberta. It is a good electric log marker (Figure 2). Hitchon (1964) computed the standard deviation of the log picks as 1.03 feet.

Elevations from 5,879 exploratory wells have been included in the structural contour map. This is one well for

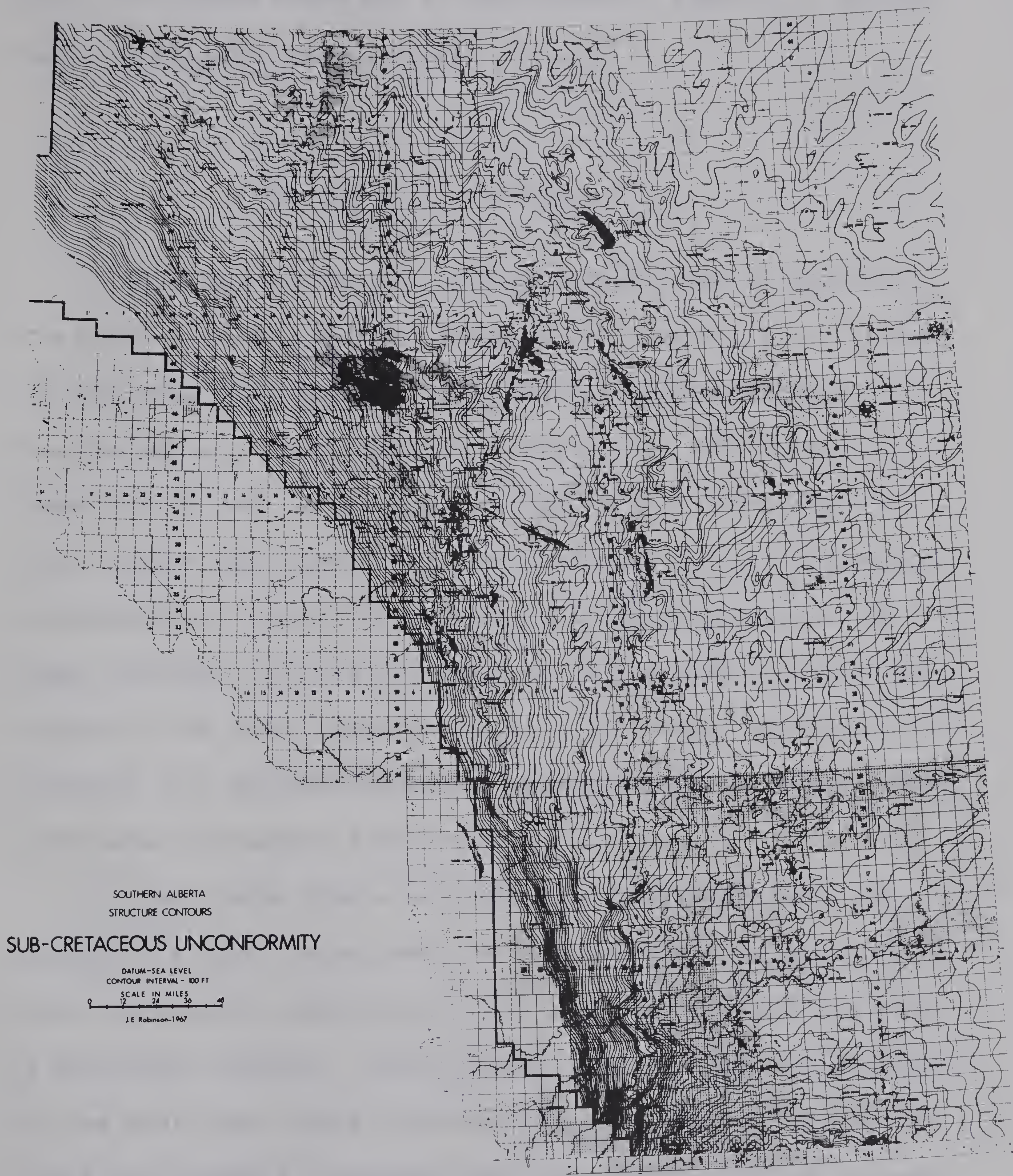
SOUTHERN ALBERTA
STRUCTURE CONTOURS
SUB-CRETACEOUS UNCONFORMITY
DATUM—SEA LEVEL
CONTOUR INTERVAL — 100 FT
SCALE IN MILES
0 12 24 36 48
J.E Robinson—1967

Figure 5

each 17.3 square miles and is approximately equal to a uniform sampling interval of 4.1 miles.

The Top of the Devonian

Throughout most of the southwestern part of Alberta the carbonates of the Upper Devonian are overlain by the shales of the basal Mississippian/Upper Devonian Exshaw Formation. The Exshaw is a black radioactive shale that varies in thickness from 35 feet in the southwestern part of the area to a thin feather edge where it subcrops against the sub-Cretaceous unconformity. Beyond the subcrop of the Mississippian, the Upper Devonian horizons are overlain by the sands and conglomerates of the basal Cretaceous. In either case, the top of the Devonian is a distinctive marker horizon that can be accurately correlated throughout southern Alberta.

The change from a very minor disconformity with the Exshaw to a major unconformity with the Cretaceous detracts from the overall usefulness of the Devonian carbonate top as a structural surface. There is also a strong regional gradient to the west that causes a decrease in well control corresponding to the rapidly increasing drilling depths required to reach the Devonian. The change from a depositional to an erosional surface also permits an evaluation of the inter-relationship between erosional and structural features. It is an excellent

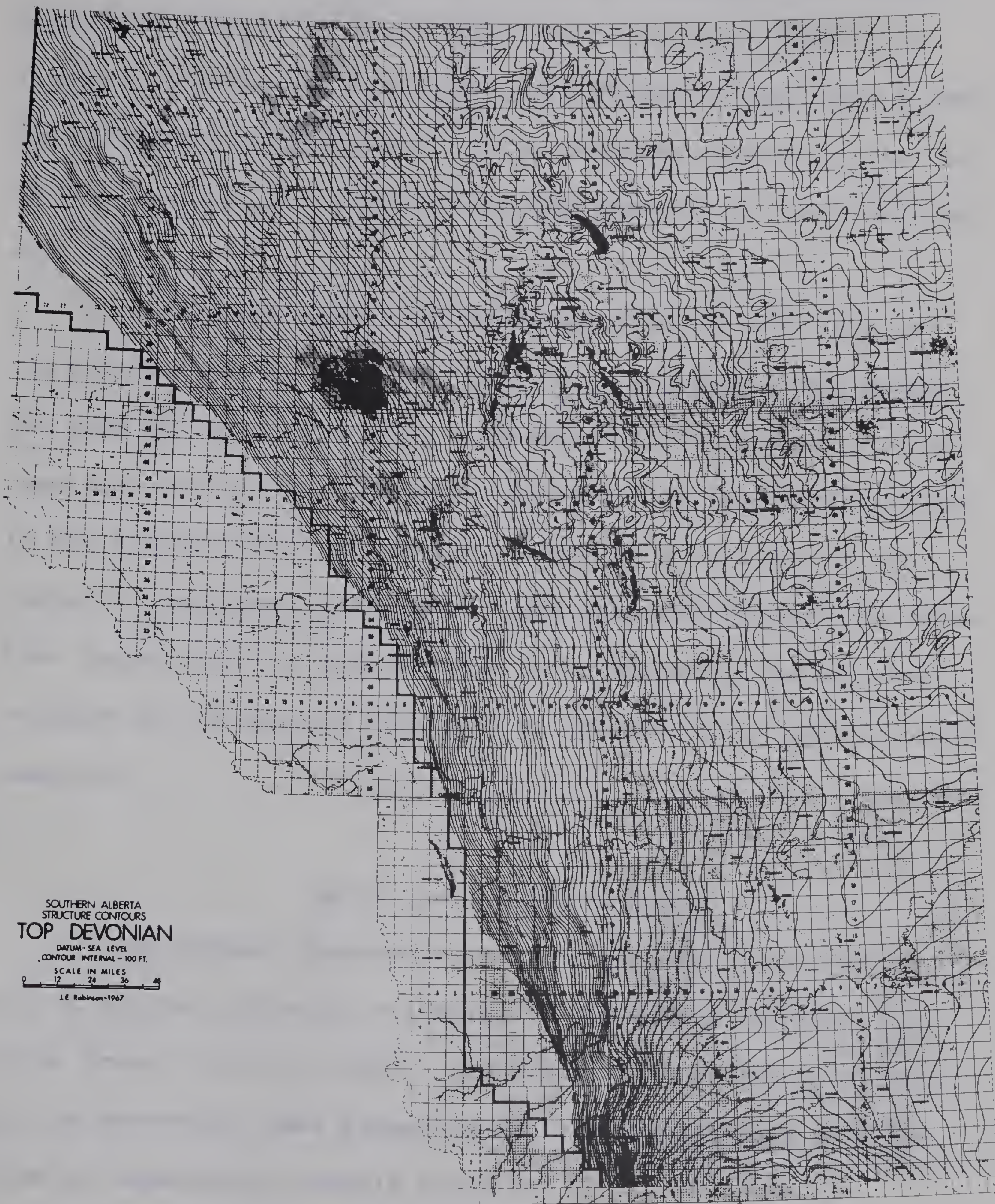
SOUTHERN ALBERTA
STRUCTURE CONTOURS
TOP DEVONIAN
DATUM - SEA LEVEL
CONTOUR INTERVAL - 100 FT.
SCALE IN MILES
0 12 24 36 48
J.E. Robinson - 1967

Figure 6

electric log marker (Figure 2) and it is estimated that under conditions similar to those described by Hitchon (1964), the standard deviation of elevation picks should be less than 5 feet. The structural contour map, the top Devonian (Figure 6), is the deepest surface used in the filtering approach to the structural analysis.

Elevations from 3,875 exploratory wells were used in the construction of the map. This is an average of one sample for each 26 square miles and corresponds to an average uniform sampling interval of 5.1 miles. However, the well distribution is not statistically random since there is a drop off in the number of locations to the west. The sampling interval is therefore larger than the average in a strip bordering the western boundary of the map and this must be considered in the structural analysis.

Top of the Elk Point Group

The deepest dependable marker that underlies nearly all of southern Alberta is the top of the Middle Devonian Elk Point Group (A.S.P.G. 1960). The group is conformably overlain by the Beaverhill Lake Formation of late Devonian age with the zone of demarcation usually indicated by the presence of dolomitic red and green shales. The Elk Point Group unconformably overlies rocks ranging in age from Silurian to Precambrian and is missing entirely from the southernmost parts of the area.

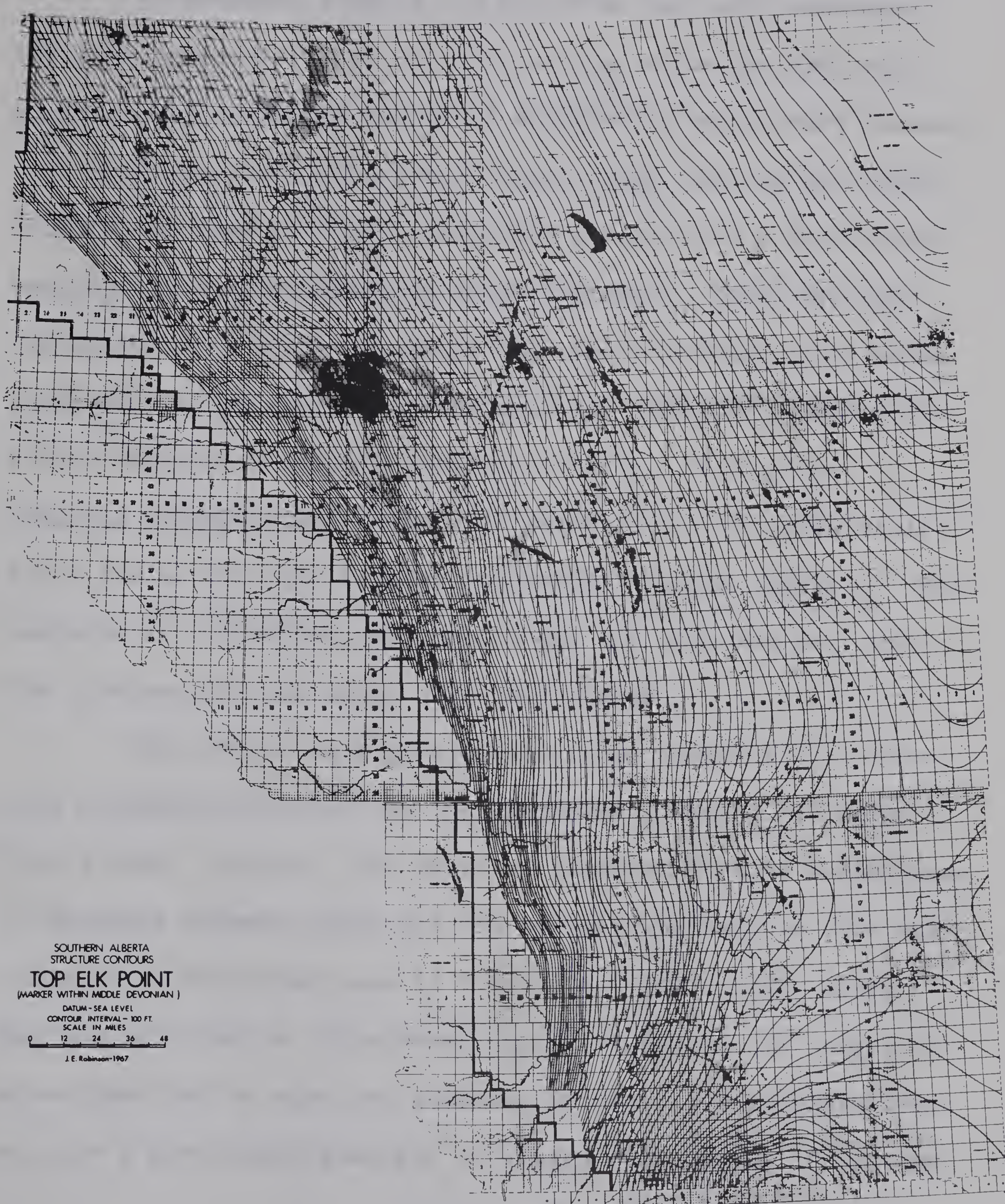
SOUTHERN ALBERTA
STRUCTURE CONTOURS
TOP ELK POINT
(MARKER WITHIN MIDDLE DEVONIAN)
DATUM - SEA LEVEL
CONTOUR INTERVAL - 100 FT.
SCALE IN MILES
0 12 24 36 48
J. E. Robinson-1967

Figure 7

In southern Alberta the horizons that are considered the most prospective for oil and gas lie above the Elk Point so that only a limited number of exploratory wells have reached this interval. The structural contour map, the top Elk Point (Figure 7), does not have sufficient control for a structural analysis of the intermediate scale features. There are only 599 exploratory wells available for use in the map which means there is only an average of one well for each 170 square miles for an equivalent uniform sampling interval of 13 miles. A sampling interval this large will reveal only the large scale and a few of the very largest intermediate scale features. The contours are therefore very smooth and the map does not show the intermediate and small scale structures.

The surface is a good electric log marker with a probable standard deviation for the elevation picks of not more than 5 feet. However, the sampling interval permits variations in accuracy between wells and the overall accuracy is poor when compared to the other maps in the suite. The top Elk Point map was included to illustrate the continuity of the large structures and to show the absolute necessity of adequate control for a structural analysis of a particular scale of feature.

Mapping Procedure

Reliable elevations with reference to a sea level datum were available for the desired horizons from all exploratory wells and it was only necessary to plot the values at the well locations and to contour the maps. Both plotting and contouring were done entirely by hand. Equivalent maps could have been produced by computer controlled mechanical means but the necessary equipment was not available.

Contouring experience suggested that a map scale of four miles to one inch and a contour interval of one hundred feet would be most suitable for hand contouring maps with the available density of control. Tests, made by trial contouring portions of the area using half the well data then measuring the resulting error between the estimated and the real elevation of the remaining wells, indicated the accuracy to be within plus or minus 50 feet. In many places, particularly where the surfaces have gentle dips, a fifty foot contour interval could have been used. However, the one hundred foot interval is the most suitable overall.

Maps of southern Alberta on a scale of four miles to one inch are too large for satisfactory presentation or for contouring in one piece. The maps were therefore contoured in segments that were aligned so that there would be good continuity across adjoining edges. After contouring, the segments were

photographically reduced and joined to produce a working suite of maps on a scale of twelve miles to one inch. This procedure permits the use of a large scale for ease in contouring and a smaller scale for presentation. The contouring was semi-mechanical so that personal prejudice in the positioning of the contours would be at a minimum. The large scale map segments were retained so that they could be used in the digitizing process.

Analytical Procedure

A structural analysis generally consists of two main parts, the geometric analysis that defines the structures and the kinematic-dynamic analysis that suggests the movements giving rise to the structures and the forces required to cause the movements. An accurate geometric analysis of a specific structure depends on the ability to measure its physical attributes with a minimum of error, even though the original structure may be distorted by conflicting structures.

A preliminary examination of the structural contour maps indicated the presence of a heterogeneous range of structural features distributed over all the surfaces that have a sampling interval of five miles or less. These structures range in size from the large scale, regional features such

as the Sweet Grass Arch, through a number of intermediate scale (minimum dimension between ten and fifty miles) to the numerous small scale crenulations that are at the limit of, or beyond the resolving power of the well spacing. The initial step in the structural analysis requires that the intermediate scale features be physically defined.

A structural contour map represents the sum of the amplitudes of all contained structures regardless of their scale. Therefore all structures conflict with each other and any specific structure will be difficult to define unless it is of sufficiently high amplitude to stand out from the general background. Unfortunately, the intermediate scale structures are of relatively low amplitude and are masked by the high amplitude large scale structures and the moderate amplitude small scale structures. The small scale structures present an especially difficult problem. Not only is their amplitude often equal to that of the intermediate scale features but their physical size can cause secondary distortion of both the intermediate and large scale features (Figure 8) by the phenomenon known as "aliasing" (see e.g. Blackman and Tukey, 1959, p. 117).

The presence of a structure can only be detected if the sample density is equivalent to a uniform sampling interval

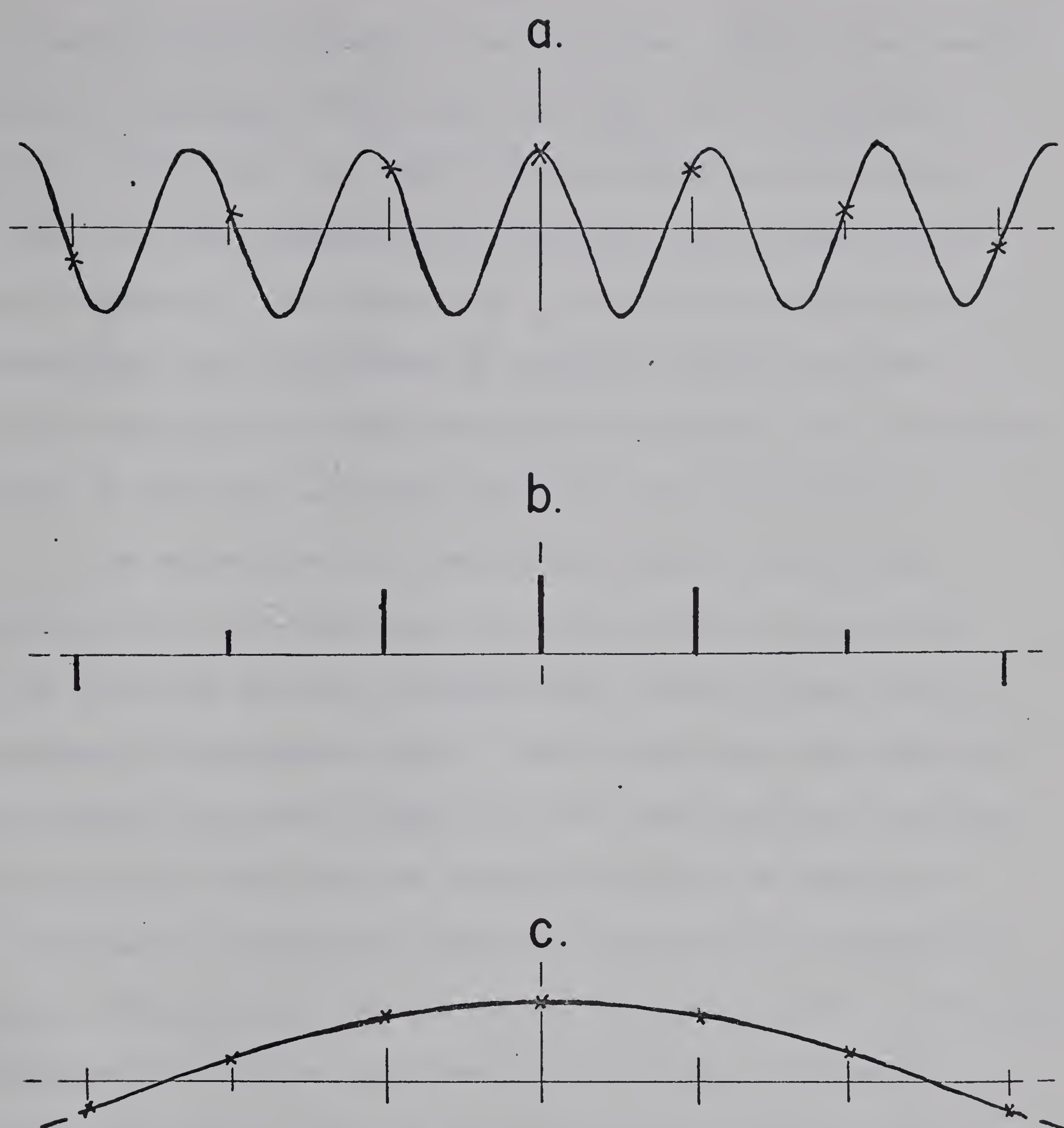

Figure 8

(a) is a sinusoidal wave uniformly sampled at less than two samples for each wave length
(b) shows the sample values
(c) is the apparent waveform resulting from the inefficient sampling

not greater than the width of the structure. Much closer sample spacing is necessary before the structure can be accurately defined. Structures too small for the sample spacing may not be seen but their presence still distorts the analysis of the larger features. This means that a geometric analysis of the intermediate scale structures of southern Alberta requires that the maps must be first processed to suppress the distortive effects of both the large and the small scale structures.

The extraction of a particular range of structural features from a heterogeneous suite of structures is similar to the filtering problem of extracting a useful signal from a background of extraneous noise. The mathematical principles of Filter Theory have been worked out for communications problems (see e.g. Lee, 1960) and the same concepts can be adapted to the problem of suppressing undesired structures in a geometric analysis of structural contour maps. The application of filtering principles to a finite two-dimensional surface is known as spatial filtering. Once the maps have been filtered, the output can be used for a limited but rigorous geometric analysis.

The rigorous geometric analysis can be amplified by extrapolated interpretation and the complete analysis can then be used to interpret the kinematic and dynamic relationships as far as they can be defined within the limits of the available

control. Finally, the composite structural analysis can be used to postulate on the geomorphic and economic significance of tectonic events in southern Alberta.

CHAPTER 2 - SPATIAL FILTERING OF STRUCTURAL CONTOUR MAPS

Introduction

Filters are generally thought of as contrivances for freeing liquids of suspended impurities, and indeed, the earliest filters were felt mats used for straining liquors. Spatial filters can similarly be considered as strainers because, through a mathematical process, they free structural contour maps of unwanted information. These filters are specifically designed to suppress the unwanted wavelengths in much the same way that electronic filters minimize noise in radio circuits. They are called spatial filters because they act on functions of distance (or space) rather than the more usual application to functions of time. In the mathematical concept, distance and time are interchangeable. Spatial filtering comes under the general discipline of Filter Theory. From among the many publications dealing with this topic are those, ranging from the non-mathematical to the rigorous, by Anstey (1965), Peterson and Dobrin (1965), Marshal (1965), Robinson and Treitel (1964) and Lee (1960).

The mathematical approach to filtering effectively began early in the nineteenth century when Jean Baptiste Joseph Fourier was able to show that any finite function of time (and thus of distance) can be represented by the sum of

a series of sine and cosine waves of specific amplitudes and frequencies. For periodic functions the Fourier series can be expressed as (see e.g. Lee, 1960, p.5)

$$f(x)=\frac{A_0}{2}+\sum_{n=1}^{\infty}(A_n \cos n\omega^1 x + B_n \sin n\omega^1 x) \tag{1}$$

and

$$A_n=\frac{2}{X^1}\int_{-X^1/2}^{X^1/2} f(x) \cos n\omega^1 x \, dx \qquad n= 0,1,2\ldots.. \tag{2}$$

$$B_n=\int_{X^1/2}^{X^1/2} f(x) \sin n\omega^1 x \, dx \qquad n= 1,2,3\ldots.. \tag{3}$$

where ω^1 in radians per the unit length, is the fundamental angular frequency and is equal to the period of the function X^1 divided by 2π and x is the independent variable. The length unit must be selected so that X^1 is an integer multiple.

If there are no restrictions on length the summation is replaced by the Fourier integral (see e.g. Lee, 1960, p.33)

$$f(x)=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)\, e^{i\omega x}\, d\omega \tag{4}$$

where ω is now the independent angular frequency (equal to 2π times the spatial frequency or wave number and to 2π divided by the wavelength) and x is the distance variable. The integral can be made to represent any curve that can be plotted on a graph in terms of amplitude and distance (e.g. a structural cross-section). The functions $f(x)$ and $F(\omega)$ are two forms of the same information. The former is what is called the distance domain, whereas $F(\omega)$ is the identical information in terms of amplitude, frequency and phase of the constituent sinusoidal waves and is in the frequency domain.

The Fourier integral can also be expressed as

$$F(\omega) = \int_{-\infty}^{\infty} f(x)\, e^{-i\omega x}\, dx \qquad (5)$$

These equations, known as Fourier transforms, permit any continuous linear function to be transferred from one domain to the other (Figure 9).

In two dimensions, any surface such as a structural contour map may be represented by the summation of sinusoidal surfaces (each of which looks like a sheet of corrugated iron) of specific amplitudes, frequencies, phases and directions. The two dimensional Fourier transforms corresponding to equations 4 and 5 are (see e.g. Swartz, 1954, p. 47)

$$f(x,y) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(\omega,k)\, e^{i(\omega x, ky)}\, d\omega\, dk \qquad (6)$$

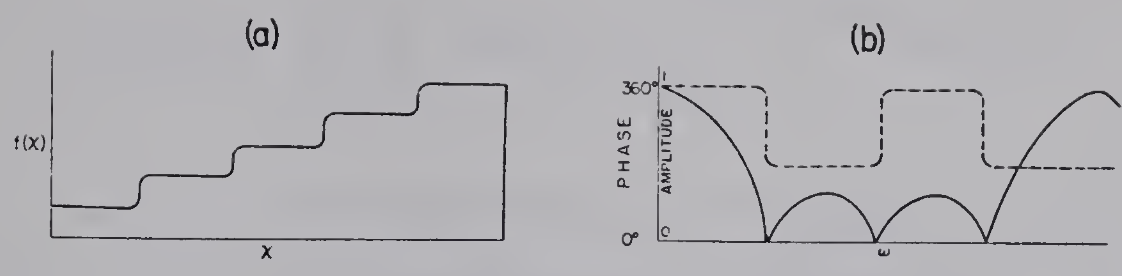

Figure 9

(a) A one-dimensional function in the distance domain.
(b) The same function in the frequency domain; both the amplitude spectrum (continuous line) and the phase spectrum (broken line) are required to display the constituent spatial frequencies.

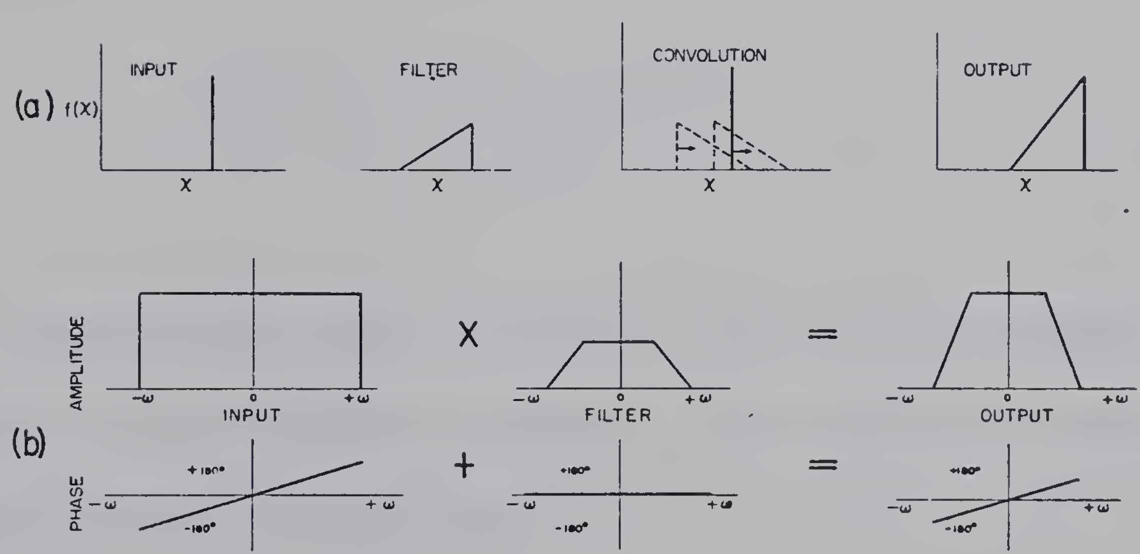

Figure 10

Filtering in two domains. (a) Convolution in the distance domain. (b) Multiplication of the amplitude spectrum and addition of the phase spectrum in the frequency domain.

$$F(\omega,k)= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y)\, e^{-i(\omega x,ky)}\, dx\, dy \qquad (7)$$

where x and y are distances in rectangular co-ordinates and ω and k, are the corresponding spatial frequencies.

Fundamentals of Spatial Filtering

The process of filtering suppresses the amplitudes of certain wavelengths in the input function (e.g. a structural cross-section) so that the filtered output essentially contains only a predetermined and desirable range of wavelengths. Filtering in the distance domain is known as convolution (see e.g. Blackman and Tukey, 1959 p. 72) and in one-dimension can be expressed as

$$O(x)= \int_{0}^{\infty} I(x-\lambda)\, S(\lambda)\, d\lambda \qquad (8)$$

where $I(x)$ is the input function, $S(\lambda)$ is the lagged filter and $O(x)$ is the filtered output. The Fourier transform of the convolution integral is

$$O(\omega)= I(\omega) \circ S(\omega) \qquad (9)$$

where $I(\omega)$ is the input function in the frequency domain, $S(\omega)$ is the filter and $O(\omega)$ is the filtered output. Filtering in the frequency domain requires only that the filter be multiplied by the input function, whereas filtering in the distance domain

necessitates folding, multiplication, shifting and summation (Figure 10).

Filtering of two-dimensional functions can also be carried out in either the distance of the frequency domains; the spatial counterpart of the convolution integral and its Fourier transform are (see e.g. Dean, 1958, p. 100)

$$O(x,y)= \int_0^\infty \int_0^\infty I(x-\tau,y-\lambda)\ S(\tau,\lambda)\ d\tau\ d\lambda \tag{10}$$

$$O(\omega,k)= I(\omega,k) \cdot S(\omega,k) \tag{11}$$

Although the two-dimensional equations are the basis for spatial filtering, they are not readily adaptable to structural contour maps in their continuous form. Spatial filtering is practical only when it is carried out on digital computers which can convolve and transform very rapidly. Digital computers accept a function only if it is approximated by a series of discrete samples taken at uniform intervals so that equations 6, 7, and 10 must be rewritten in digital form. Integration can be approximated as closely as desired by the summation of very closely spaced data points taken over the limits of the variable. Structural contour maps have finite areas so all values beyond their edges can be considered as zero. Therefore, the digital two-dimensional Fourier transforms become (Gentleman and Sande, 1966, p. 564)

$$f(x,y)= \frac{1}{4\pi^2} \sum_{\omega=0}^{a-1} \sum_{k=0}^{b-1} F(\omega,k)\, e^{\frac{i(\omega x+ky)}{ab}} \qquad (12)$$

$$F(\omega,k)= \sum_{x=0}^{a-1} \sum_{y=0}^{b-1} f(x,y)\, e^{\frac{i(\omega x+ky)}{ab}} \qquad (13)$$

and the digital form of spatial convolution is

$$O(x,y)= \sum_{x=0}^{a-1} \sum_{y=0}^{b-1} I(x-\tau,y-\lambda)\, S(\tau,\lambda) \qquad (14)$$

Filter Theory and Geology

The application of spatial filtering to geological maps can be described in non-mathematical terms. The main premise, (employing the principles of the Fourier series) is that any geological cross-section or contoured map can be duplicated by adding together a specific number of sinusoidal waves or surfaces (Figure 11). Large scale structures are composed mainly of long wavelength sinusoids while small scale structures contain only the short wavelengths.

A structural contour map represents a frequency domain presentation and is the sum of all constituent sinusoids. The individual sinusoids are displayed in the frequency domain. The amplitude spectrum of the individual sinusoids shows their wave-length and height while the phase spectrum illustrates their position with respect to the origin (ordinate). The

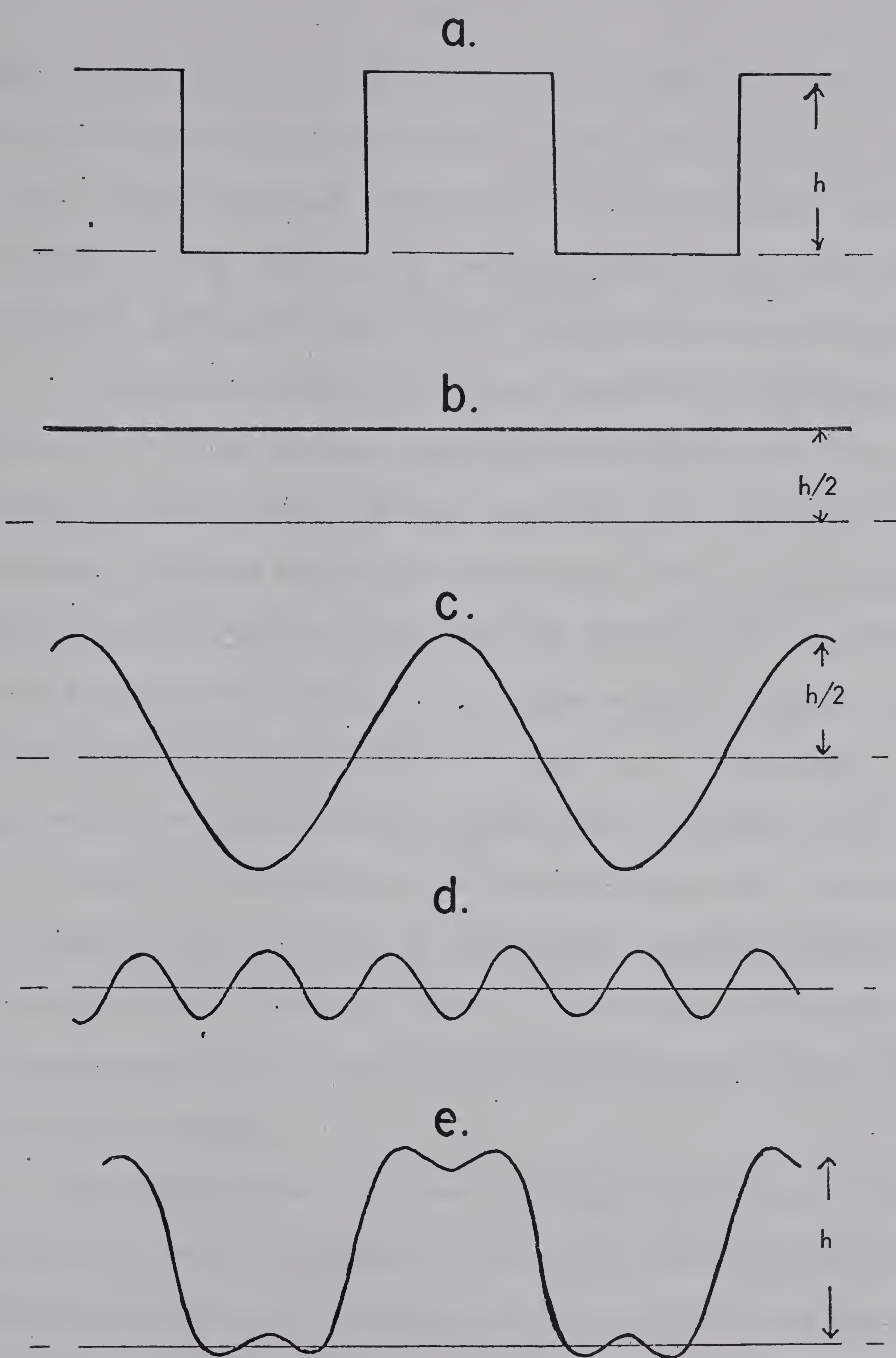

Figure II

(a) is a symmetrical function.
(e) is the approximation of (a) produced by the addition of the average elevation (b) and sinusoids (c) and (d).

phase of a sinusoid is a measure of the offset of a maximum from the origin, zero phase occurs if the maximum is at the origin. Since the phase (position) of the sinusoidal surfaces is related to the location of the structures on the map, spatial filters for geological maps do not change phase relationships.

The actual filtering process, whether it is called convolution in the distance domain or multiplication in the frequency domain, simply changes the amplitudes of some of the sinusoidal surfaces that make up the map. If the sinusoids that comprise a specific structure are reduced, the amplitude of the structure is reduced by the same amount. Spatial filtering enhances the interpretation of particular structures by suppressing the amplitudes of conflicting structures that fall outside of the desired size range (Figure 12). The process is similar to the action of an automobile suspension where the springs and shock absorbers filter out the short wavelength road undulations while passing the long wavelength bumps and hills without change.

Geologists have long been familiar with forms of filtering in their use of regional, residual and trend surface maps. Spatial filtering can be looked upon as a sophisticated and mathematically rigorous approach to the problem of producing valid regional and residual maps.

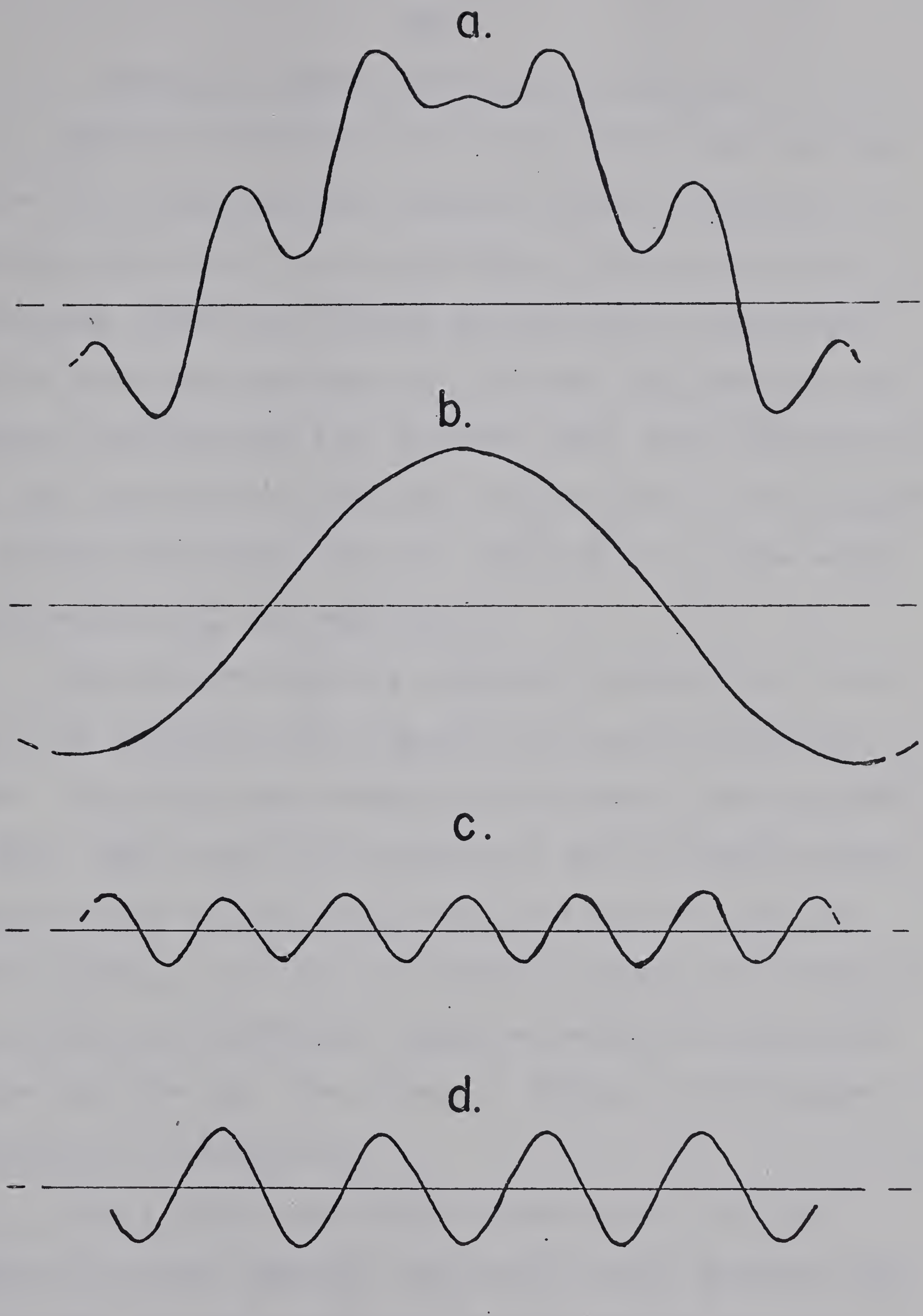

Figure 12

(a) is a composit waveform. If it is passed through a filter so that (b) and (c) are deleted, the output will be (d).

History of Spatial Filtering and Geology

Spatial filtering of structural contour maps was first carried out by smoothing the contours visually to produce regional maps without local variations. Contouring of the differences between the original and the smooth map produced residual maps that displayed only the small and therefore high frequency features (see e.g. Levorsen, 1927; Rich, 1935a and b). This fast and effective technique is still widely used although the surface and residual maps are influenced to a large extent by the person doing the smoothing.

Filtering methods were improved by geophysicists working on the interpretation of magnetic and gravity potential fields. One method uses potential field theory (see e.g. Grant and West, 1965, chap. 8) to construct a grid of equally spaced weighted values that can be overlain on a map with the same sample spacing. A new map is produced by taking the average of the products of coincidental values as the grid is moved step by step over the map. The process is similar to convolution and produces a filtered map.

Peters (1949) calculated averaging grids for both upward and downward magnetic continuation, while Henderson and Zietz (1949) did the same for the second vertical derivative of a magnetic field. Griffin (1949) compared various grids used for computing gravity residuals. Nettleton (1954) summarized the various graphical and derivative methods for computing

averaging grids and noted the strong similarity to electrical filtering.

Swartz (1954) demonstrated that a contoured map could be described mathematically by a two-dimensional Fourier Series. Dean (1958) used the basic principles of filter theory to derive the relationship between gravity and magnetic potential fields and their derivative maps. Danes and Oncley (1962) used harmonic analysis to describe the filtering effect of several common second derivative averaging grids and compared them on the basis of their frequency spectra. Bhattacharyya and Raychaudhuri (1967) have used two-dimensional filters to compute the equivalent of residual and derivative magnetic maps.

Trend analysis of structural contour maps (Krumbine 1959) is another approach to filtering that also has its roots in geophysical interpretation. Agnocs (1951) computed regional maps by fitting a number of least squares, best fit, first order polynomial surfaces to segments of gravity potential maps. Simpson (1954) used a digital computer to fit first to fourth order polynomial surfaces to equally spaced gravity data. Oldam and Sutherland (1955) used orthogonal polynomials to compute the surfaces. Grant (1957) introduced the term "Trend Analysis" and discussed methods of computing polynomial surfaces for both equally spaced and random data.

Krumbine (1956) investigated the adaption of geophysical surface fitting methods to geological interpretation and Miller

(1956) hand calculated best fit surfaces for several sedimentary environments. Krumbine (1959) used a digital computer to fit first and second order polynomial trend surfaces to randomly spaced geological data. Miller and Kahn (1962), Krumbine and Graybill (1965) and Merrian and Cocke (1967) have discussed many of the applications of trend analysis to geological problems.

Trend surfaces and their residuals are important tools for geological interpretation and computer programs for deriving first to sixth order surfaces have been published (Harbaugh, 1963; Good, 1964; O'Leary, Lippert and Spitz, 1966). However, even trend surface computations are beginning to be influenced by Fourier techniques. Harbaugh and Preston (1965) used a two-dimensional Fourier expansion on structural data with a uniform sampling interval to approximate a polynomial trend surface. James (1966) fitted two-dimensional Fourier series to irregularly spaced data.

The principles of spatial filter theory were described by Swartz (1954) and Dean (1958). Holloway (1958) designed one-dimensional filters for smoothing time series and two-dimensional filters for smoothing contoured maps. Zurflueh (1967) applied spatial filters to geophysical data and illustrated how filtering can smooth topographic maps. He also pointed out the advantages of spatial filtering over polynomial trend surfaces.

Gentleman and Sande (1966) wrote programs for fast Fourier transforms that are very useful in harmonic analysis and spatial filter design.

The present technique of spatial filtering requires uniformly spaced input data but its many advantages over the older filtering methods make it very useful for geological interpretation. The output from spatial filtering contains only a predetermined range of structural features whose width, amplitude and trend can be defined mathematically. Filtered maps can be compared directly and even used to construct isopachs if the average elevation has been retained. Where the average elevation has been deleted by the filtering process, the subtraction of one surface from the other produces negative anomalies in place of the usual thicks and thins. The result is an "Apostreptic" map instead of the more usual isopach. Apostreptic is derived from a Greek adjective referring to a divergence from the normal.

Distance and Frequency Domain Filtering

Spatial filtering is apparently much simpler in the frequency (equation 9) than in the distance domain (equation 14). It is only necessary to compute the two-dimensional Fourier transform of the input map, delete any undesired frequencies and carry out the inverse transform. The output from the latter transform is the filtered map.

Unfortunately it is very difficult to obtain an accurate transform of a map surface from normal digital elevations without some preliminary adjustments. The problems can be illustrated by considering the one-dimensional Fourier transform of a structural cross-section.

The amplitude and phase spectrum of a cross-section consists of the sum of all spectra from the structures contained in the section. This sum includes the spectrum of the average elevation plus the spectrum of the abrupt discontinuities caused by any difference in elevation between the two ends of the section (Figure 13).

Since only the geological structures are to be filtered it is necessary to eliminate the effects of all other components before transforming to the frequency domain. Most of the unwanted effects can be removed by subtracting the average elevation and windowing the section (see e.g. Blackman and Tukey, 1958, p. 77) but this causes frequency domain filtering to become a

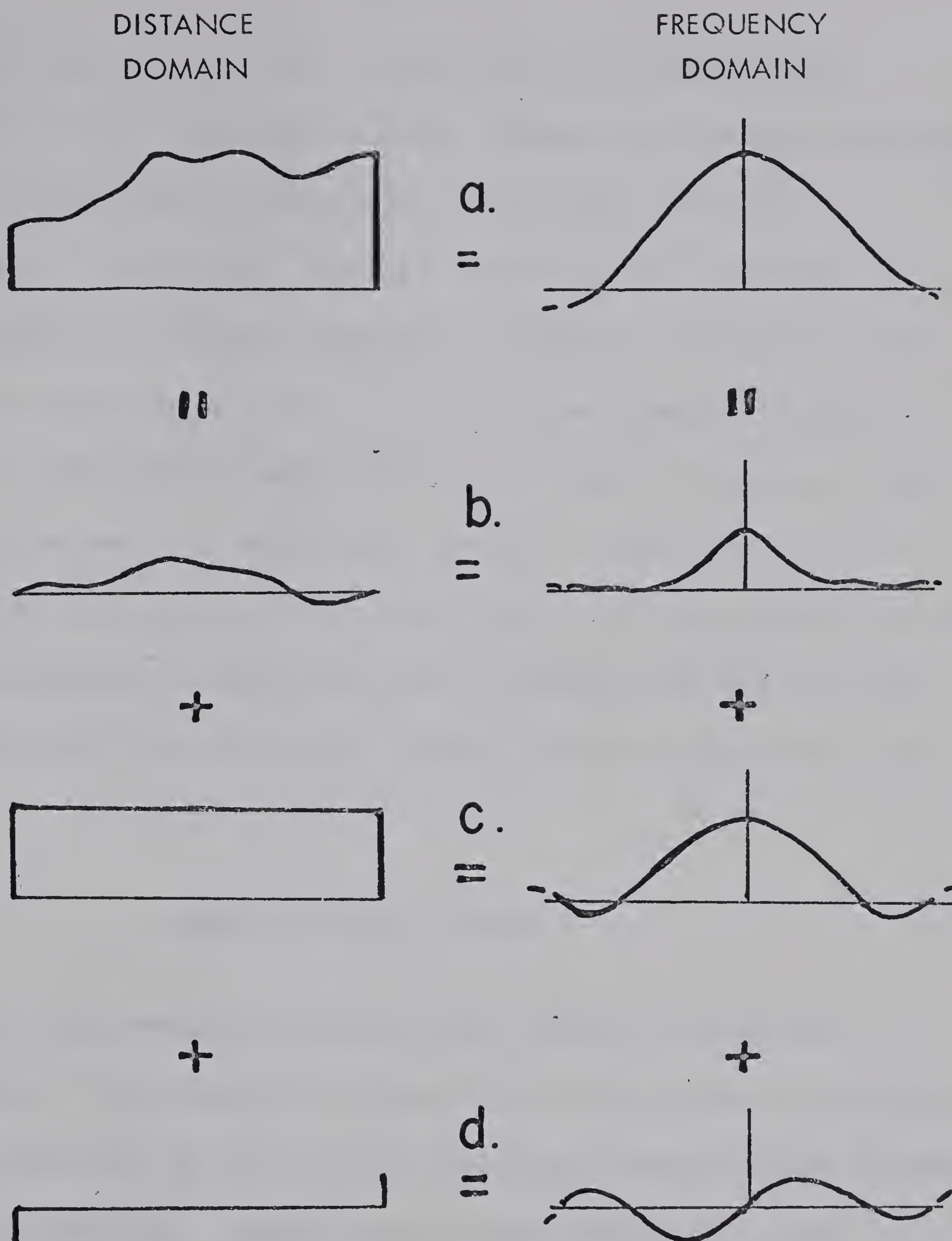

Figure 13

(a) is a structural cross-section and its amplitude spectrum.
(b) shows the geological structures.
(c) is the average elevation and (d) is the effect caused by differences in elevation at the ends of the section.

longer and more complicated process than one-dimensional convolution in the distance domain. There are similar problems with two-dimensional filtering of structural surfaces.

Thus, in general, spatial filtering of structural contour maps on a digital computer is faster and simpler when carried out by convolution in the distance domain. Spatial filters for geological maps are usually small in area and can easily be checked for mechanical errors. Since they act on only a limited portion of the map at any one time, edge effects are at a minimum and large maps can be segmented and filtered separately with only one-half a filter width required for overlap.

Spatial Filter Design

In one-dimensional structural cross-sections the amplitudes of the component frequencies can be shown to determine the relief of the structural features, whereas phase determines their location. Similarly, in two dimensions, phase determines both position and orientation of the structural features. Therefore, the phase characteristics of the input map must not be altered during filtering; to do so would be equivalent to moving the structures and changing their orientation. Phase angles are additive in the filtering process (see e.g.

Anstey, 1965, p. 30), therefore no phase changes occur if all phase angles in the filter are zero.

A complex continuous one-dimensional frequency function $F(\omega)$ can be separated into its real and imaginary parts (see e.g. Lee, 1960, p. 34):

$$F(\omega) = P(\omega) + iQ(\omega) \tag{15}$$

where $P(\omega)$ and $Q(\omega)$ are real and are the components making up the complex function $F(\omega)$. The amplitude spectrum $|F(\omega)|$ and the phase spectrum $\theta(\omega)$ are given by

$$|F(\omega)| = \sqrt{P^2(\omega) + Q^2(\omega)} \tag{16}$$

$$\theta(\omega) = \tan^{-1} \frac{Q(\omega)}{P(\omega)} \tag{17}$$

where the phase of a particular frequency is the angle with which the waveform leads or lags an arbitrarily designated zero origin. Now $\theta(\omega)$ will equal zero if $Q(\omega)$ equals zero and for the filter, $F(\omega)$ must then equal $P(\omega)$. From Euler's identity

$$P(\omega) = \int_{-\infty}^{\infty} f(x) \cos \omega x \, dx \tag{18}$$

similarly in two-dimensions

$$P(\omega,k) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x,y) \cos \omega x \cos ky \, dx \, dy \tag{19}$$

so that zero-phase filters consist entirely of cosine terms. Since cosines are even functions, one-dimensional filters must have bilateral symmetry about the zero origin. The symmetry of two-dimensional filters must be at least orthorhombic. Such filters suppress structural features on the basis of both wavelength and direction. Spatial filters that suppress structural features on the basis of wavelength alone have axial symmetry.

Spatial filters should be designed expressly to suppress unwanted wavelengths. Therefore, the first step in the construction of a spatial filter is to determine what wavelengths are present in the original structural contour map and their respective amplitudes. This can be done by computing one-dimensional amplitude spectra (see e.g. Blackman and Tukey, 1959, p. 90) for two or three cross-sections that give a statistical representation of the structures present. The phase spectrum need not be known, for spatial filters are specifically designed to have zero-phase characteristics. The sections should be sampled at very close intervals because a particular wavelength will appear in its proper position in the amplitude spectrum only if it is longer than twice the sampling interval (see e.g. Goldman, 1953, p. 67); wavelengths too short for the sampling interval appear as aliased additions to the amplitudes of longer wavelengths. Consequently, if the sampling interval

is too large the shorter wavelengths are not detected and the relative amplitudes of the longer wavelengths incorrectly estimated (see e.g. Peterson and Dobrin, 1966, p. 14).

The spatial filter is designed in the frequency domain as follows. The one-dimensional amplitude spectra from the selected cross-sections are averaged to obtain a statistically valid estimate of what wavelengths are prominent in this original contour map. The large scale structures are represented mainly by the long wavelengths. Spatial filters can be designed to enhance any structure with a width greater than the digitizing interval. However, the frequency pass-bands should not be terminated abruptly, since there is usually a considerable overlap in the frequency ranges of the various structures.

The amplitude spectrum of the filter is so designed that multiplication by the average amplitude spectrum of the cross-section produces the desired output amplitude spectrum (Figure 14). The amplitudes in the filter are set equal to one for wavelengths that are to be passed unchanged, and smoothly reduced to zero where wavelengths are to be suppressed or terminated. Changes in the filter amplitude spectrum should be smooth, since abrupt corners produce undesirable side effects in the finished filter. This one-dimensional amplitude spectrum is a cross-section through the axially symmetrical two-dimensional filter. The complete two-dimensional frequency domain

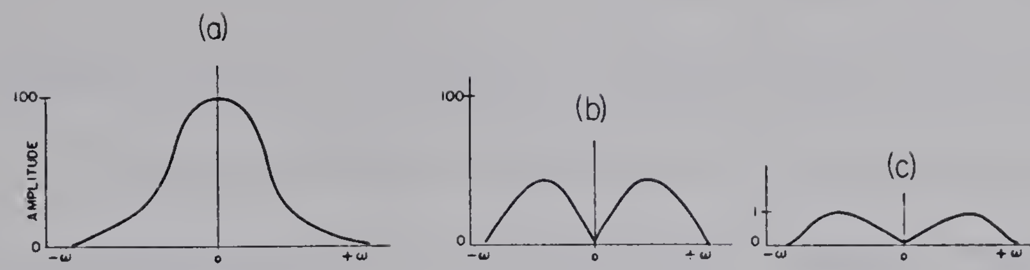

Figure 14

Filter design in the frequency domain. (a) Average amplitude spectrum of three cross-sections from the map in Figure 6. (b) Desired amplitude spectrum. (c) Amplitude spectrum of the zero phase filter required to produce (b).

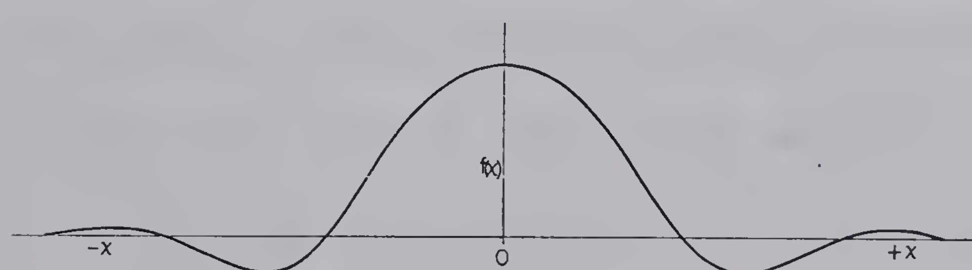

Figure 15

Cross-section through a two-dimensional band-pass spatial filter.

filter is then constructed, digitized and transformed by equation (12) to arrive at the two-dimensional spatial filter.

Theoretically, spatial filters extend to infinity. However, if the amplitude spectrum of the filter is smoothly rounded, the amplitude of the distance domain transform becomes and remains negligible a short distance from the origin so that the filter can be safely truncated at the second or third zero crossing. The size of the final filter depends on the frequency range it is designed to pass:narrow band filters are large in a real extent whereas wide band filters are small. Transformation to the distance domain is carried out on a digital computer with the spatial filter in digital form. However, the filter can be considered as a continuous two-dimensional function if it needs to be redigitized (Figure 15). When the average elevation of the original structural contour map (the zero frequency) is to be passed unchanged, the sum of the filter weights should equal unity. If the average elevation is to be removed, the sum of the weights should be zero.

Truncation of Spatial Filters

The distance domain transform of a band limited frequency function has infinite length. If the function is to be used as a spatial filter it must be truncated at a convenient and practical distance from the origin. Unfortunately truncation can alter the frequency spectrum of the filter and considerable care must be taken to ensure the alteration is kept within tolerable limits.

The degree of alteration can be determined by taking the inverse Fourier transform of the truncated filter and comparing it with the original spectrum. Iterative checking is slow but it can be kept to a minimum if the original frequency spectrum has been carefully designed.

This filter distortion can be illustrated (Figure 16) by considering the inverse transforms of a one-dimensional rectangular frequency function that has been abruptly truncated. If there is a sharp cut off at a value other than zero, the inverse transform has negative side lobes that in the frequency domain constitue phase inversions (see e.g. Blackman and Tukey, 1958, p. 68). Truncation at a zero crossing prevents phase distortion but there is still a considerable change from the original rectangular spectrum.

If the original frequency spectrum is rounded so its ends have a gaussian or a cosine shape (see e.g. Blackman and Tukey, 1958 p. 95), the amplitude of the distance domain transform becomes and remains negligible within a reasonable distance from the origin. When this happens it can then be safely truncated with a minimal effect on the frequency spectrum (Figure 17).

The tapered frequency spectrum also has other advantages. Geological structures vary in size and there is usually considerable overlap in their frequency spectra and the contribution of individual features can only be determined in very general terms. Consequently any sharp termination of the frequency

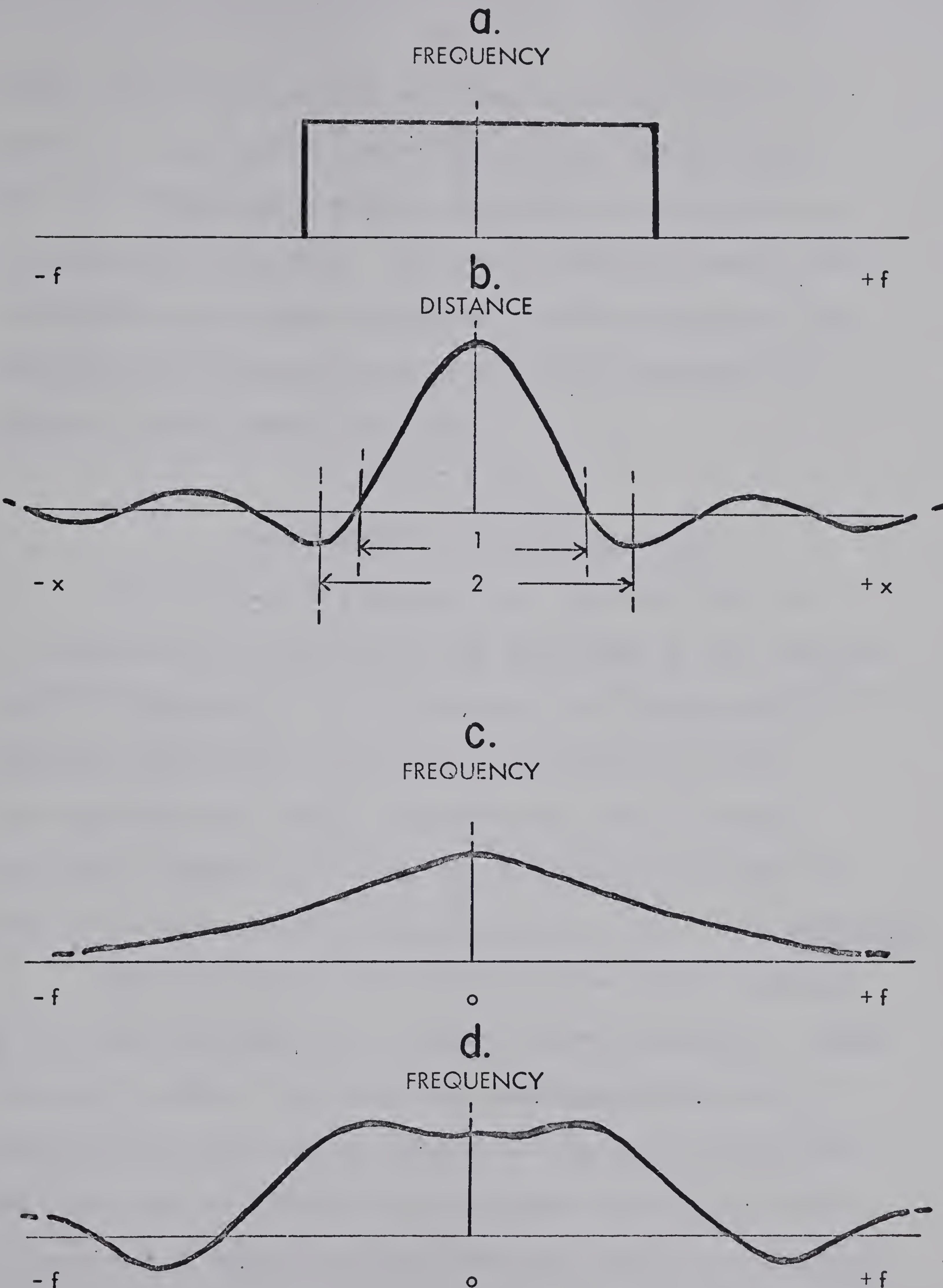

Figure 16

(a) is an amplitude spectrum and its freauency domain transform (b)
(c) is the inverse transform of the distance function truncated at 1.
(d) is the inverse transform of the distance function truncated at 2.

domain filter would be very arbitrary and more difficult to justify on a geological basis than a broad tapered filter with its fundamental frequency determined from the width of the desirable structures. The filter frequency spectra with tapered ends is the most desirable from the theoretical and the geological viewpoints and is therefore considered the optimum form for spatial filters.

Amplitude of Filtered Structures

The relief of a structure on a contoured map can be considered as a function of the amplitudes of its component spatial frequencies. If the structure is filtered and all frequency (wavelength) components are retained in their true magnitude the output structure will retain its real amplitude. However, if any of the component amplitudes are reduced the filtered structure will also be reduced in amplitude.

Edge loss in filtered maps requires severe rounding of the amplitude spectrum to prevent phase distortion. Therefore, only a few of the frequency components making up the desired structures will be retained at their true amplitude and there will be a reduction in apparent structural relief. If there are a variety of structures, the reduction in relief will not be uniform but will be less for those structures with

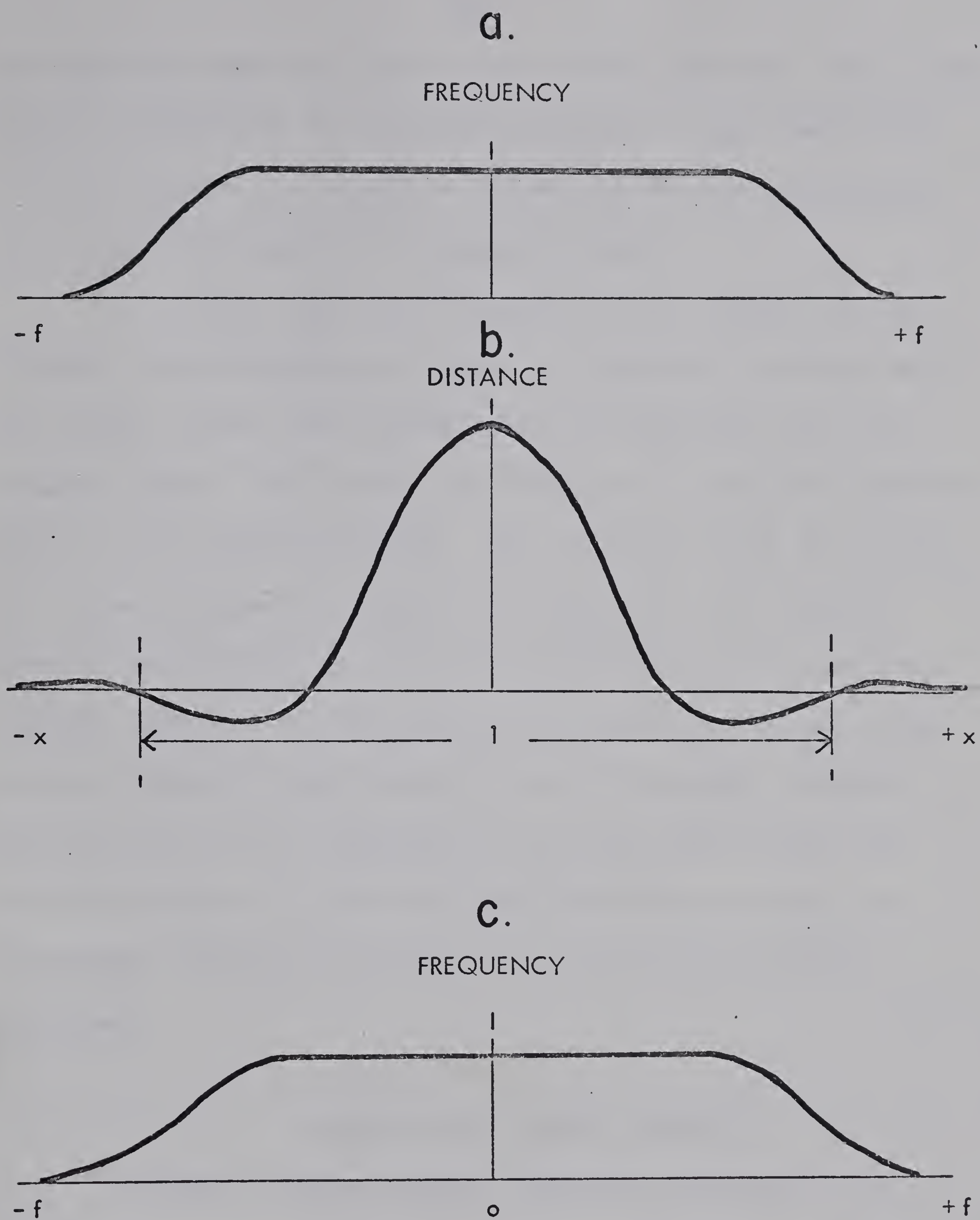

Figure 17

(a) is a smoothly terminated amplitude spectrum and its distance domain transform (b)
(c) is the inverse transform of the distance function terminated at 1.

an amplitude spectrum close to the filter spectrum. This means that the amplitude of structures retained in most geological filtered maps is not absolute and should only be considered as a relative measure of structural relief.

It is not practical to restore true relief, but the filters can be adjusted to output the desired structures with an average relief that is realistic by comparison with the original maps. This is done by changing the gain (or amplific-ation) of the spatial filter. The filtered output structures can be made larger or smaller by multiplying the distance domain coefficients by a factor proportional to the desired change. Since all coefficients are changed by the same prop-ortion, bandpass characteristics are not altered. However, distortions that are negligible in a unity gain filter can become important if they are highly amplified and must be considered whenever the relief of a structure is greatly increased.

Directional Spatial Filters

Spatial filters normally suppress wavelengths and therefore structures regardless of their orientation. How-ever, if the undesired features have a strong directional trend, filters can be designed that suppress structures on the basis of their orientation as well as wavelength. Directional spatial filters can remove conflicting structures

in the same size range as the desired structures providing there are distinct angular differences in trend.

Design requirements for directional spatial filters are similar to the requirements for the non-directional ones in that they must have zero phase characteristics and there should not be any abrupt discontinuities in the frequency domain amplitude spectrum. A frequency domain directional filter (Figure 18) looks like the ordinary two-dimensional non-directional filter but with wedge shaped slices symmetrically removed from about the ω axis. The angle of the zero amplitude represents the angular range, but not the direction, of the structures that will be suppressed. This frequency domain filter is then transformed into the distance domain for use in the actual filtering operation.

The zero phase characteristics of the directional filter can be shown from a consideration of the two-dimensional digital frequency to distance transform for zero phase conditions. From equation 19 the digital zero phase transform can be written

$$f(x,y)= \frac{1}{4\pi^2} \sum_{\omega=0}^{a-1} \sum_{k=0}^{b-1} P(k,\omega) \cos \omega x \cos ky \qquad (20)$$

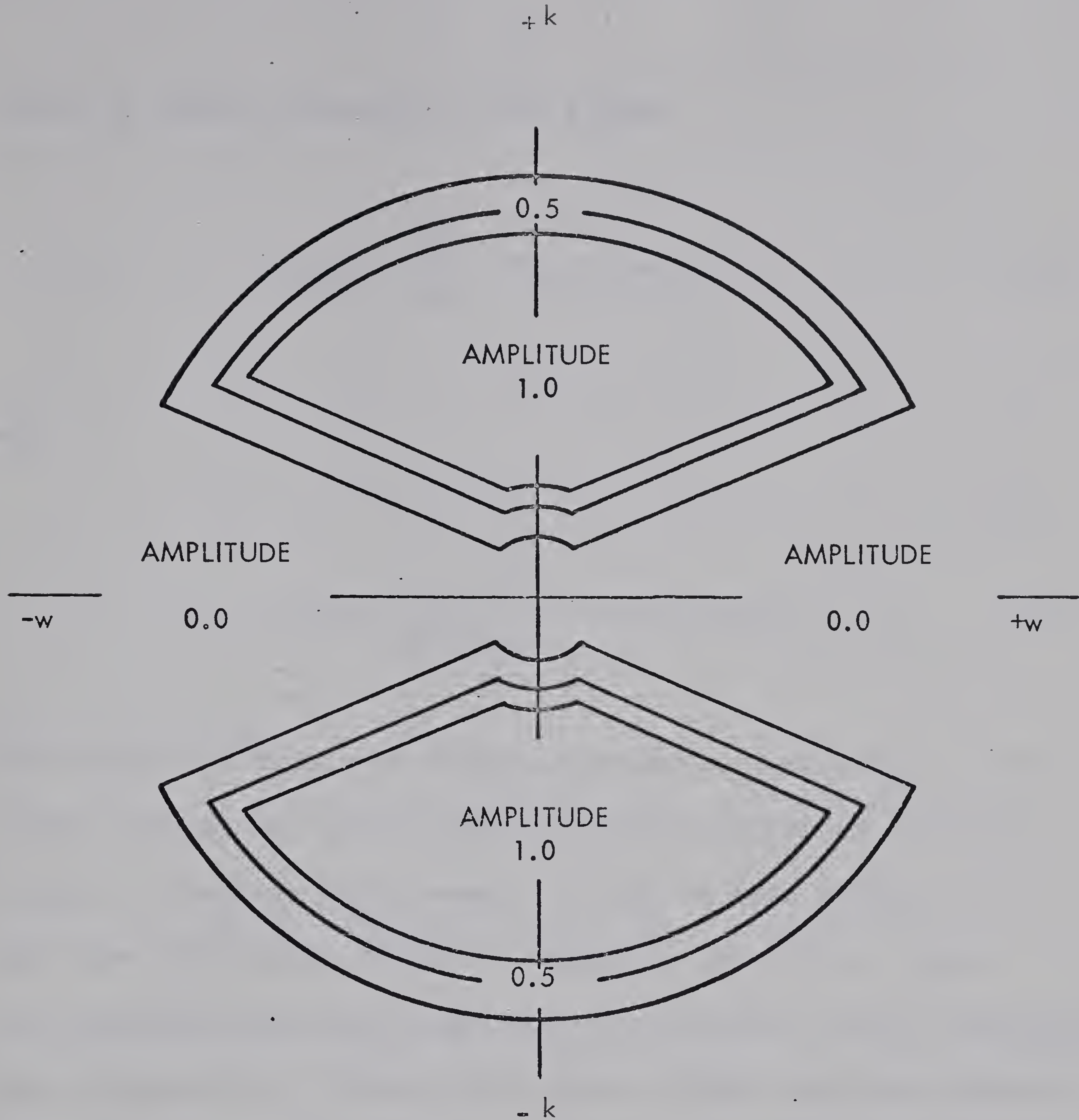

Figure 18

The amplitude spectrum of a directional, two-dimensional band pass filter.

which is usually computed in two stages

$$H(x,k) = \sum_{\omega=0}^{b-1} P(k,\omega) \cos \omega x \tag{21}$$

and

$$f(x,y) = \frac{1}{4\pi^2} \sum_{k=0}^{a-1} H(x,k) \cos ky \tag{22}$$

This means the matrix of frequencies can be transformed, first of all, row by row and the results then transformed column by column to complete the process. It can be seen (Figure 18) that the directional filter is symmetric about the k axis so individual rows are symmetrical functions and their transforms must be symmetric. Since the original filter was also symmetric about the ω axis it follows that the symmetry will be retained in the partial transform and in the second stage, column by column transform that produces the completed two-dimensional distance domain function. Symmetrical functions are cosine functions and therefore the two dimensional directional filter will have the necessary zero phase characteristics.

After transformation to the distance domain the

directional filter is truncated and aligned to suppress wavelengths with a specific direction. Now, however, the folding part of convolution, which was neglected for the non-directional filters must be included in the convolution of directional filters. Accurate alignment of the directional filter is critical so it is advantageous to align the filter with the map exactly and carry out the folding manually before the directional filter is digitized. This manual process not only minimizes errors but allows the same relatively simple convolution program to be used for both directional and non-directional spatial filtering.

Spatial Filtering Procedure

The first step in the spatial filtering of a structural contour map is to compute the amplitude spectra of two or three closely sampled cross-sections. From these spectra and from an inspection of the map, the filter is designed as previously described. The next step is to digitize the filter and the map. The optimum digital interval depends on both the average spectrum of the cross-sections and the frequency range of the filter. For convenience the digital interval should be as large as possible without distorting the filtering process. If the digital interval for the cross-sections is short enough the average amplitudes will decrease as the wavelengths decrease.

Although some leeway is permissible, the best digitizing interval is half that wavelength beyond which the amplitudes of shorter wavelengths are more than an order of magnitude smaller than those in the filter passband (Figure 19). Once the input map and the filter have been digitized the convolution can be carried out.

Digital convolution implies folding, multiplication, summation and shifting. However, linear filters have axial symmetry and most spatial filters have bilateral symmetry so that folding, which is a reversal of the filter, can be neglected. Therefore, filtering of cross-sections requires only that the digitized filter be superimposed on the section. Corresponding values are then multiplied and totalled to arrive at a new value which is the filtered output for the centre position of the filter. The filter is then shifted one digital interval and the process repeated until the filter has been moved along the entire section. Spatial filtering is done in much the same way, although in this case both map and filter are in matrix rather than linear form. As all values beyond the borders of the map are considered to be zero, the filtered output has meaning only when the filter does not cover any of the zero values. This means that a zone equal to half the width of the filter is lost from the edges of the map area. Consequently narrow band filtering of small or narrow map areas is impractical.

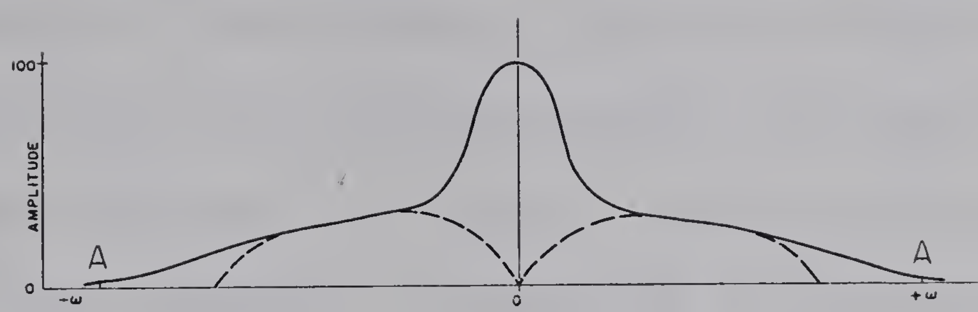

Figure 19

Average amplitude spectrum of three cross-sections from the map in Figure 6 (solid line) and the desired output spectrum (broken line). Wavelengths shorter than A can be ignored for their amplitudes are less than a fiftieth of the amplitudes in the filter pass range. The wave-length at A is two miles, so that map was digitized at an interval of one mile.

The filtered computer output can be arranged in a format that duplicates the shape of the original structural contour map so that by photographic reduction the filtered map will be on the same scale as the original. If a two-dimensional plotter is available, the filtered map can be plotted directly on the scale of the original. Since the filtered output varies smoothly and has a uniform spacing, the spatially filtered maps are adaptable to computer contouring programs and if sufficient equipment is available the production of the new maps can be entirely mechanical.

Example of Spatial Filtering

The spatial filtering method was given a preliminary test on the southernmost portion of the structural contour map on the sub-Cretaceous unconformity (Figure 20). This surface was chosen because it exhibits a wide variety of structural features including some that are known to have a tectonic origin (see e.g. Russell, 1932).

An examination of the original map suggested the presence of some structural features, ten to twenty miles in width and trending either NE/SW or NW/SE, but partially masked by strong regional gradients and numerous small scale structures. The map examination was complimented by a study of an average amplitude spectrum compiled from a harmonic analysis of three cross-sections of the area that had been digitized

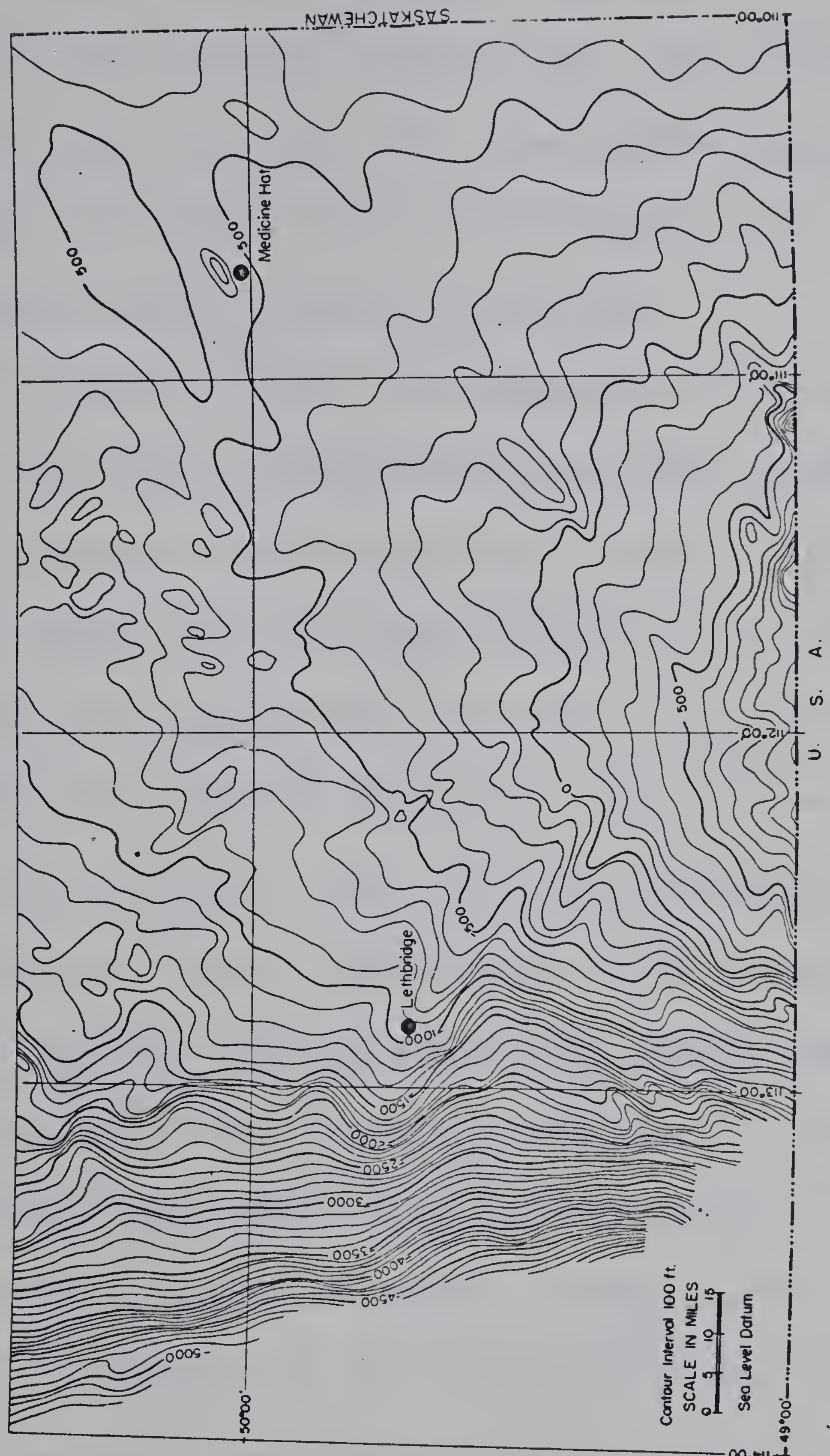

Figure 20

Structural contours on the sub-Cretaceous unconformity of southern Alberta.

a quarter mile interval (Figure 19). The combined analysis suggested that a new map with wavelengths limited to those between eight and eighty miles would display the intermediate scale structures to the best advantage.

A spatial filter was designed in the frequency domain to pass the required wavelengths and then transformed by digital computer into the distance domain. The amplitude spectrum showed that the amplitudes of wave-lengths less than two miles are insignificant so that the map and filter were digitized on a one mile interval. The computer was then used to convolve the filter with the map, producing a new spatially filtered map in which the effects of the long-wave length regional features and the short-wave length small scale structures have been virtually eliminated (Figure 21). The intermediate scale structures are now readily apparent and can be described in terms of relief, length, width and direction.

A comparison of the original and filtered map shows that the retained features are still in their correct position and have their original shape. Spatial filtering has not moved or distorted the desired features, it has only eliminated the undesired ones. The test map also indicates that the majority of the intermediate scale structures have a minimum dimension greater than ten and less than forty miles. This new information on the size of the structures suggests that it would not have

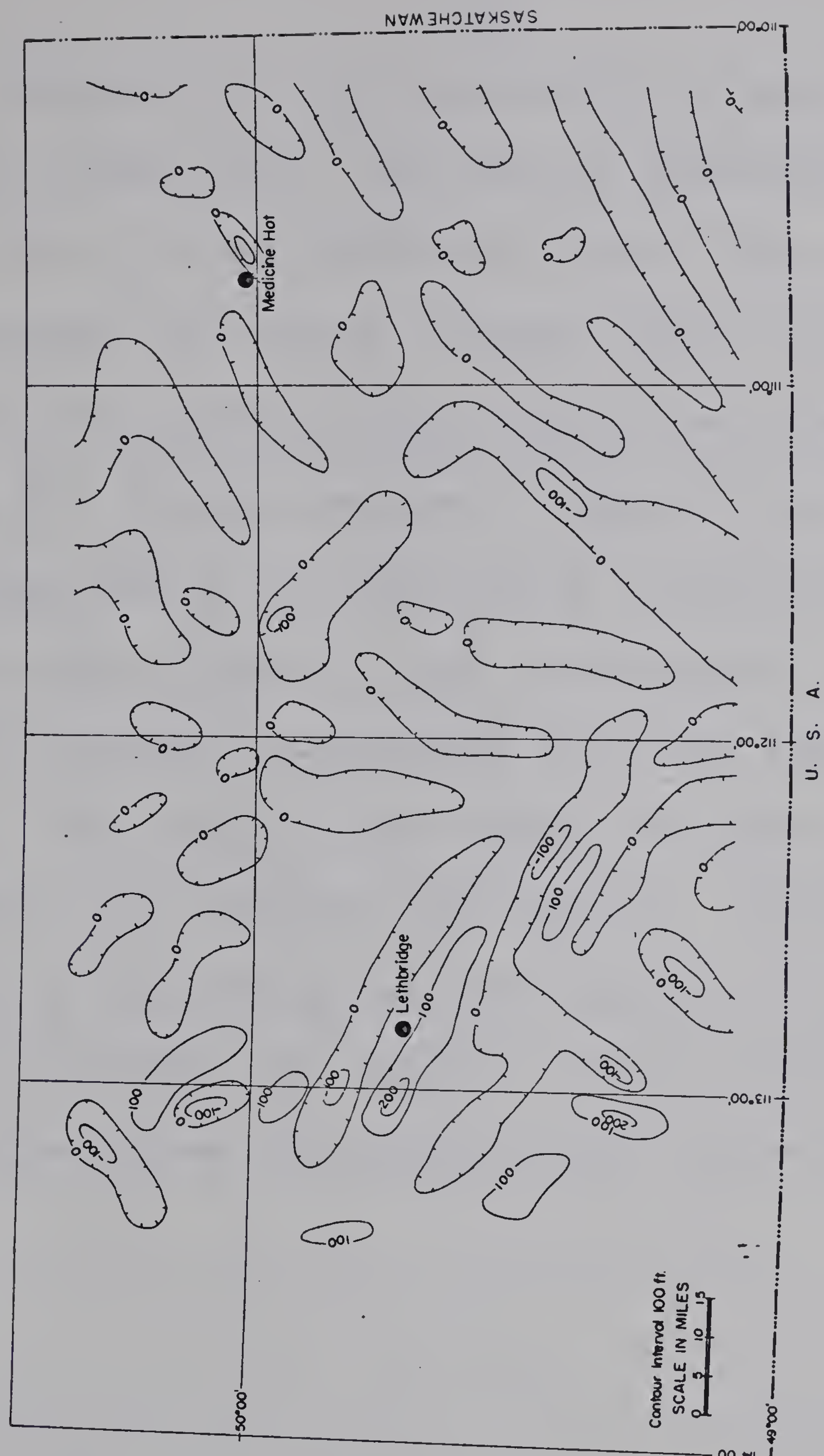

Figure 21

Filtered output from the map in Figure 6. Wavelengths between eight and eighty miles have been retained.

been necessary to retain wavelengths as short as eight miles in the filtered map. The absolute amplitude spectrum shows that if only those wavelengths longer than ten miles were to be retained, the digital interval could be increased from one to two miles without unduly harming the filtered output. This means that the work required to digitize and filter the remaining maps need be only one quarter of that required to maintain the one mile interval. Such a preliminary test, using a small digital interval is advisable in any new area.

The spatial filter passes the desired structures and appears to be relatively satisfactory. However, the final stages of determining the best filter are iterative and similar filters, with slightly modified passbands, should be tested before the optimum filter for the area is chosen.

CHAPTER 3

PROCESSING OF SOUTHERN ALBERTA STRUCTURAL CONTOUR MAPS

Introduction

Structural contour maps of a particular stratigraphic horizon include the algebraic sum of all movements that have affected it since its formation. Therefore, structural contour maps from several horizons from the same area can be used to determine the timing of these movements, providing their effect can be accurately measured on each map and separated from original depositional relief. Accurate measurement requires that the analytical techniques must be applied uniformly to each map in the group and all data processing procedures (such as spatial filtering) must be designed to apply to the group and not to individual units.

For spatial filtering to be effective, the filter design should take into account the amplitude spectrum of the desired structures and the useful part of the amplitude spectrum of the maps. The map amplitude spectrum can be considered useful for all wavelengths longer than twice the uniform equivalent well spacing. The amplitude spectrum of the structures present in the map cannot be accurately determined. However, for any particular structure it can be estimated to extend over at least one octave (an interval of frequencies, the higher

of which is double the lowest) on either side of a center frequency with a wavelength approximately equal to twice the minimum dimension of the structure.

To ensure reasonable definition of all desired structures in a spatially filtered map, the original map must have a uniform equivalent well spacing of at least two wells for each minimum dimension (width) of the smallest of the desired structures. Structures smaller than this may be present but they will be only partially defined in the original maps and in any filtered output.

Intermediate scale structures are defined as those with a minimum dimension of between ten and fifty miles. Thus only structural contour maps with a uniform equivalent well spacing of five miles or less can be considered for processing with spatial filters designed to accentuate the intermediate scale structures. Therefore, of the following five structural contour maps of southern Alberta only the first four are suitable for spatial filtering in terms of the intermediate scale structures.

a. The top of the First White Specks. (Well interval 3.7 miles)

b. The base of the Fish Scale sandstone. (Well interval 3.9 miles

c. The sub-Cretaceous unconformity. (Well interval 4.1 miles)

d. The Devonian top. (well interval 5.1 miles)

e. The top of the Elk Point. (well interval 13 miles)

Frequency Analysis

The initial step in the design of a spatial filter is to determine the frequency content of the filterable maps. This was done by computing a number of one-dimensional amplitude spectra that represent the structural features of the southern Alberta horizons. Amplitude spectra for the various maps were computed using Computer Program 1 (Appendix) from cross-sections positioned to intersect the most prominent structures in each of the three scales and digitized to a series of uniformly spaced discrete elevations. The individual spectra were then combined and their envelope used as a composite amplitude for spatial filter design. The use of the envelope of the individual spectra assures that potential filter design problems caused by local high amplitude structures will be included in the composite amplitude spectrum.

A preliminary examination of the original structural contour maps suggested that the large scale features are fairly uniformly represented but the small scale ones are more numerous and prominent on the sub-Cretaceous unconformity. Small scale structures contribute mainly to the high spatial frequencies and therefore influence the digital interval for the maps as the high frequency portion of the spatial filter.

They may also require a digital interval that is as close as one tenth of the well spacing for evaluation and for this reason a trial cross-section on the sub-Cretaceous unconformity was digitized on a one-quarter mile spacing and its amplitude spectrum computed. The results for the full map confirmed the findings in the test area (Figure 16) and the relatively small amplitude in two mile wavelength vicinity suggested that a one mile digital interval would be sufficient for the remaining sections.

Two additional sample spectra from the sub-Cretaceous unconformity and one from each of the remaining maps were computed (Figure 22) using the one mile digital interval and combined into a composite spectrum (Figure 23). The envelope for the composite spectrum was obtained by connecting the points of maximum amplitude of the superimposed individual spectra.

Spatial Filter Design for Southern Alberta

Spatial filters are designed in the frequency domain by computing the multiplication factors required to produce the desired amplitude spectrum from the composite amplitude spectrum of the input maps. An ideal spatial filter should selectively pass only those frequency components that make up

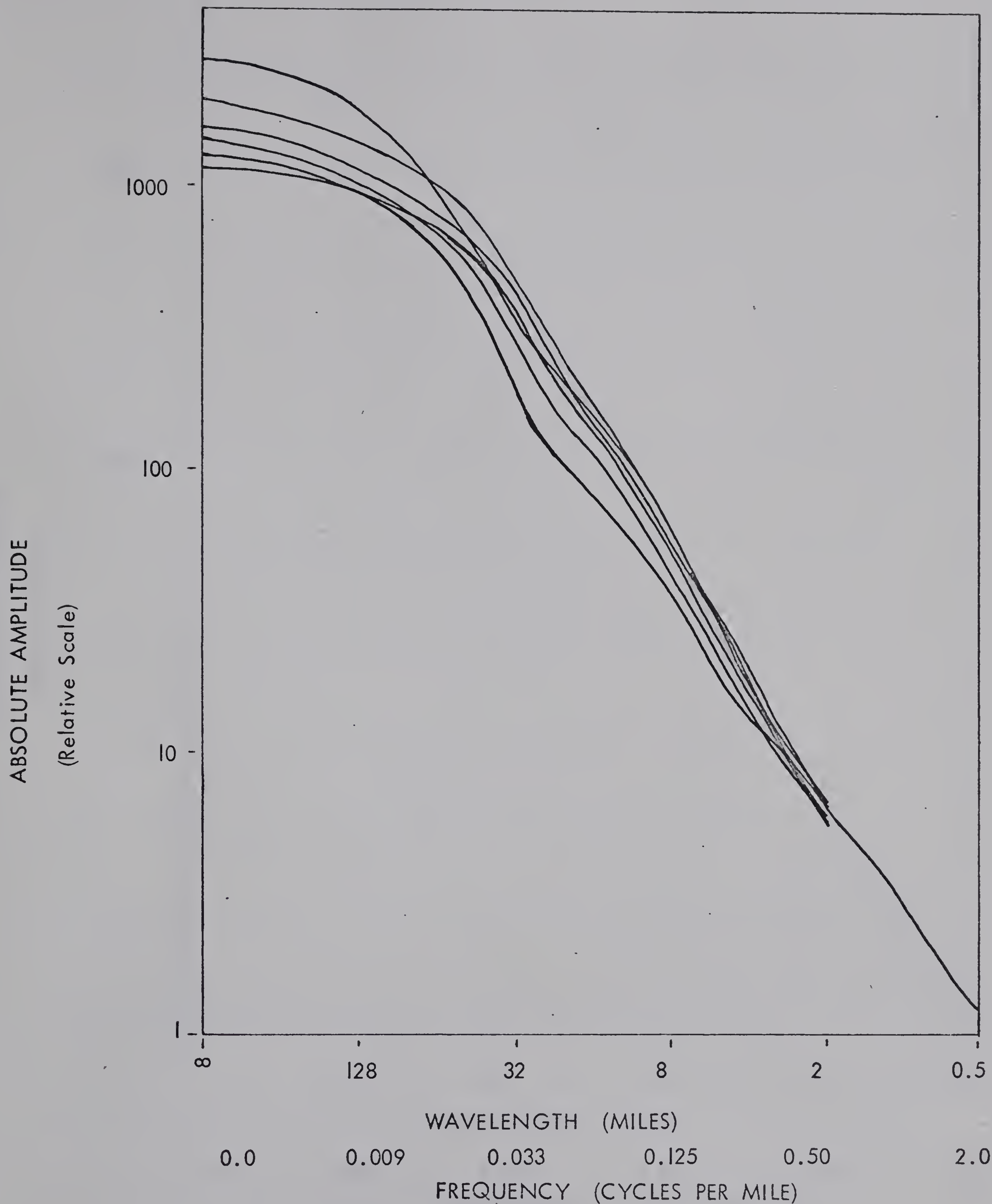

Figure 22

One-dimensional absolute amplitude spectra computed from cross-section selected from the structural contour maps of Southern Alberta. The spectra are symmetrical about the origin.

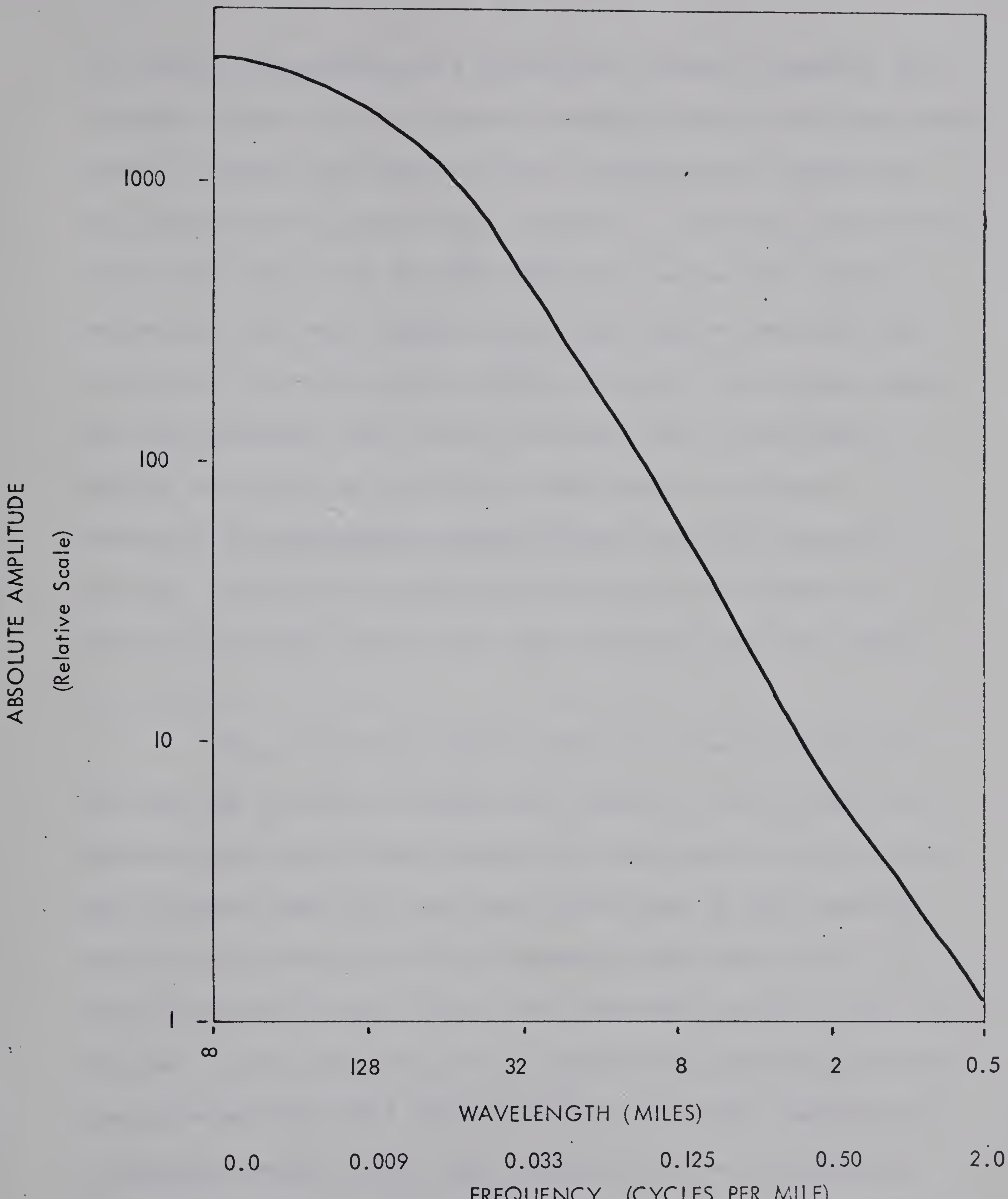

Figure 23

Composite amplitude spectrum of the structural contour maps of Southern Alberta obtained from the individual spectra of Figure 19 by connecting points of maximum amplitude.

the desired structures and eliminate all others. However, the frequency ranges of the different scales of geological structures usually overlap and there is no way of selectively apportioning components of a particular frequency. The amplitude spectrum of the map and of the desired structures can be only roughly estimated. The best spatial filter that can be designed from a study of the composite amplitude spectrum, the original maps and even a single trial filter, is still only an estimate. Whether or not it is the best estimate must be proven by comparing its performance against other similarly estimated filters. A rigorous mathematical technique for optimizing a spatial filter has not as yet been developed (Zurfleuf, 1967, p. 1019).

The structural contour maps of southern Alberta and the test map (Figure 21) apparently contain a variety of intermediate scaled structures between ten and twenty miles in width. This suggests that the high amplitudes shown in the composite amplitude spectrum for all wavelengths longer than fifty miles are caused by the large scale features and should not be retained in the filtered output. Since there should be at least some intermediate scale contribution to the longer wavelengths, a frequency domain filter that is tapered to smoothly reduce the amplitude of all wavelengths longer than fifty miles seems to be advisable. The low cut was placed at approximately the eighty mile wavelength. The high or short wavelength cut off,

was placed at approximately fourteen miles so that the smooth rounding of the frequency spectrum would not conflict with the ten mile wavelength defined by the maximum uniform equivalent well spacing of five miles. The first spatial filter was therefore designed to pass wavelengths between fourteen and eighty miles (Figure 24) thus assuring that all intermediate scaled structures with a width between seven and forty miles would appear in the output and the known, ten to twenty mile width structures, would be reasonably well defined.

The estimated one-dimensional frequency domain filter was expanded to two-dimensions, digitized to a convenient interval and transformed into the distance domain (Figure 25) using Program 2 (Appendix). To complete the filter, the distance domain function was truncated at the second zero crossing and digitized on the same interval as the maps. The sum of the digital weights were made equal to zero. However, before being used as a filter, the digital function was transformed back into the frequency domain to ensure that the original frequency spectrum had been retained.

Additional filters were required to make sure that a satisfactory filter had been designed. However, since the comparison filters only required the frequency spectrum to be shifted so that they bracketed the original filter spectrum advantage was taken of the reciprocal nature of the distance

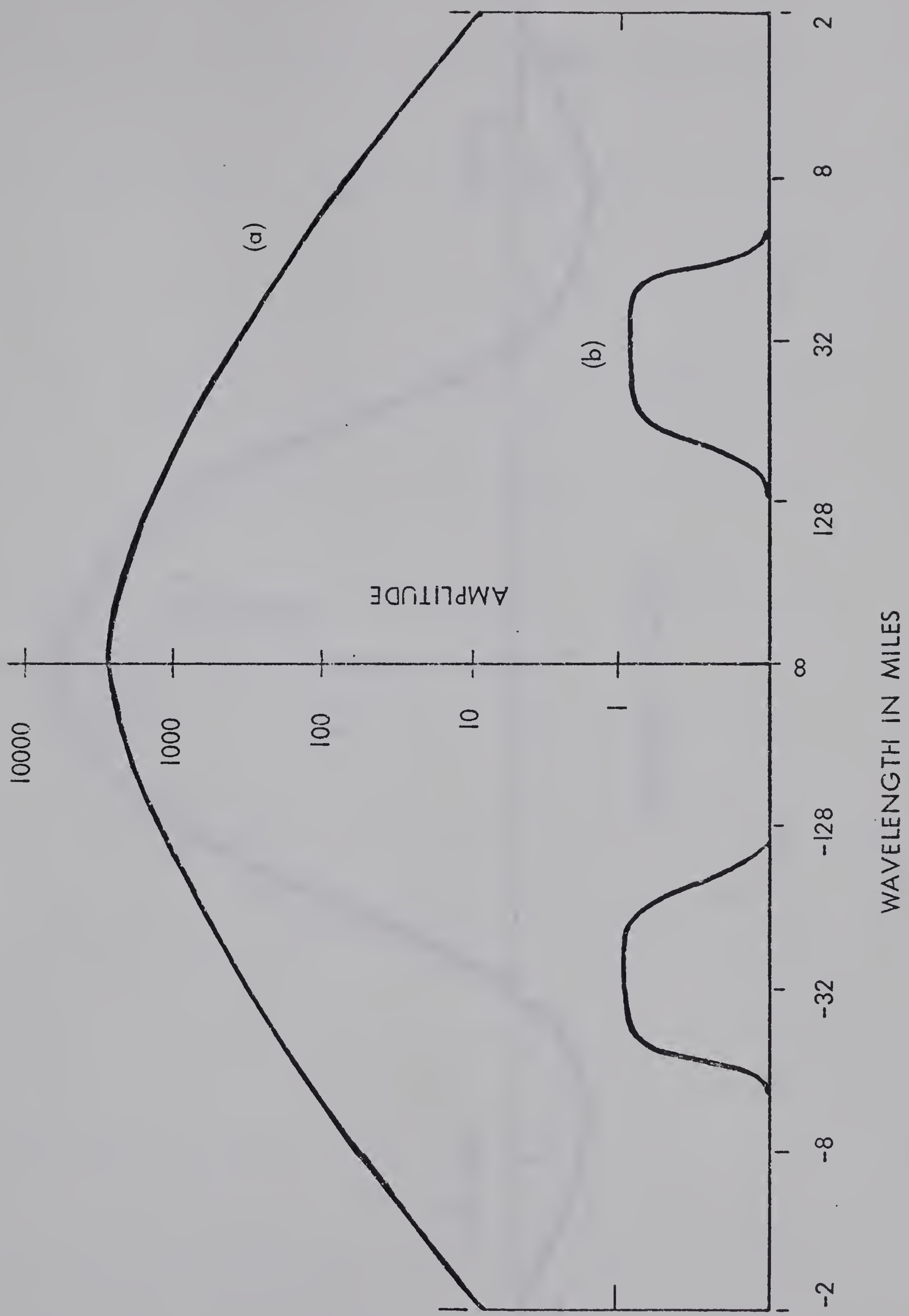

Figure 24

(a) Is the composite amplitude spectrum for southern Alberta.
(b) Is a section from a frequency domain spatial filter that will retain wavelengths between fourteen and eighty miles.

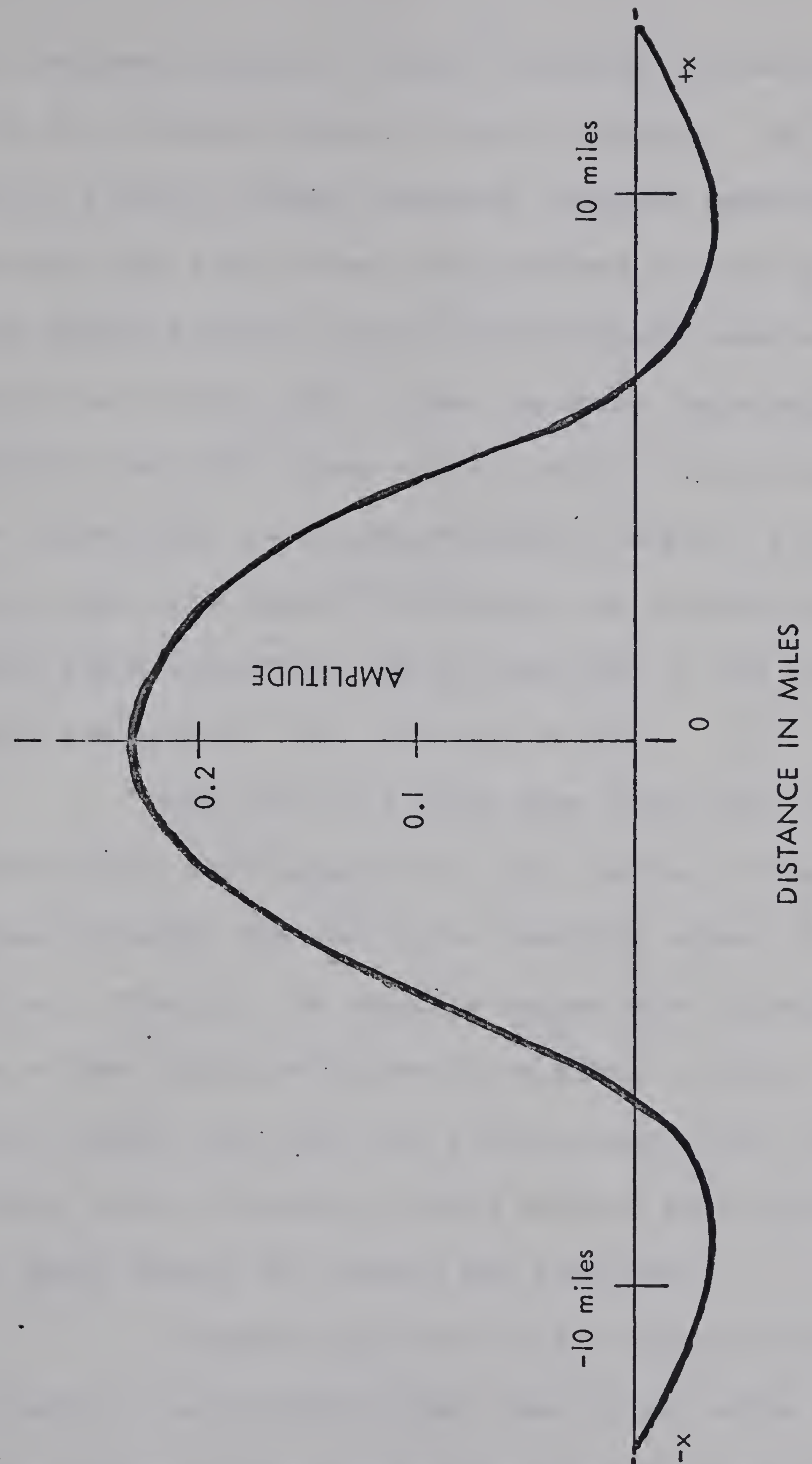

Figure 25

Distance domain cross-section of the frequency domain filter in Figure 21.

and frequency scales to simply re-scale the new filters from the original distance domain function. One new filter with a slightly higher frequency passband (wavelengths between ten and sixty miles) was produced by scaling the distance domain function over a proportionally smaller area. A second new filter with a lower passband (wavelengths between eighteen and one hundred miles) resulted from considering the filter area to be proportionally larger. A third new filter was also scaled to evaluate the contributions of the small scale structures and the shortest of the intermediate scale wavelengths (six to thirty miles).

When the new filters were digitized, the new coefficients were adjusted so that the sum of the positive values equalled the sum of the positive values of the original filter. Finally, the negative values were adjusted so that the sum of the total coefficients was equal to zero. This procedure insured that each new filter would, like the original filter, have a frequency domain maximum amplitude of unity and would delete the average map elevation.

A regional spatial filter (Figure 26) was designed to pass all wavelengths longer than thirty miles as an additional check on the premise that the high amplitude longer intermediate wavelengths are part of the large scale features. Intermediate scale structures with widths greater than twenty-five miles should be noticeable in the output from this filter.

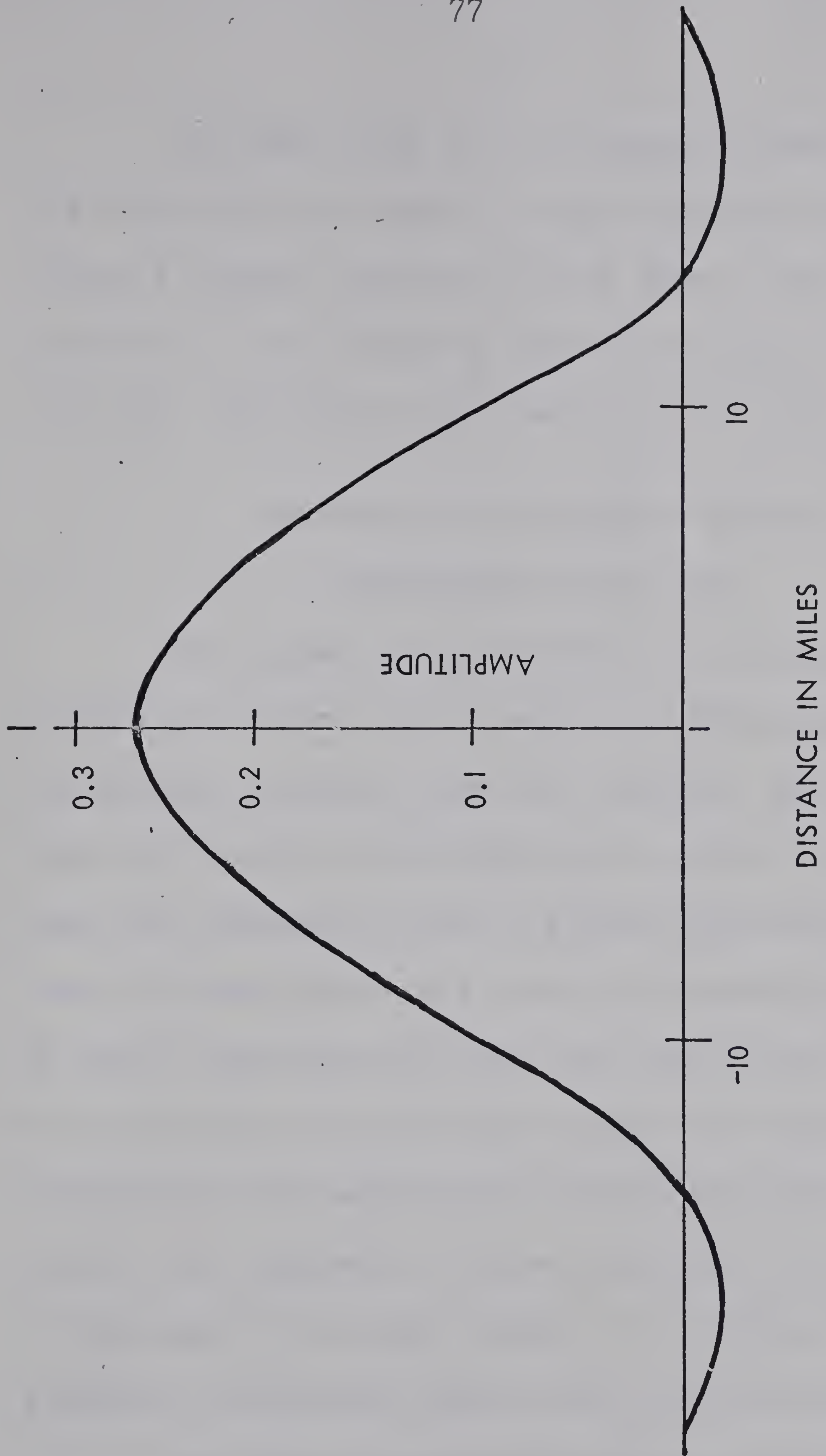

Figure 26

Distance domain cross-section of a regional filter that will retain all wavelengths longer than thirty miles.

The basic form of the frequency domain spatial filter was used with the composite amplitude spectrum to determine a suitable digital interval for the maps. This interval is a function of both frequency spectra and must be worked out before the final digitization and testing of the filters.

Digitization of Southern Alberta Structural Contour Maps

The highest frequency that can be accurately determined in a structural contour map has a wavelength equal to twice the sampling interval (see e.g. Goldman, 1953, p.67). Frequencies with shorter wavelengths may be present in the maps but they only appear as false or aliased additions to the amplitudes of lower frequencies (see e.g. Blackman and Tukey, 1958, p. 117). The composite amplitude spectrum and the contouring on the southern Alberta maps suggest that they will contain frequencies with wavelengths considerably shorter than the useful limit imposed by the well spacing. The digital interval of the maps is the main control on the effect that the short erroneous wavelengths have on the filtered output.

The digital interval should be as large as possible to assure minimum processing effort, providing the error introduced by the large interval remains within tolerable limits. A

useful empirical rule is that the amplitude of any aliased frequency within the retained frequency band width should be at least one order of magnitude less than that indicated by the composite amplitude spectrum. In this way, any error caused by aliasing (a folding of the amplitude spectrum about a frequency with a wavelength of twice the sampling interval) will be less than that caused by the original and unavoidable errors in the mapping system.

The composite amplitude spectrum of southern Alberta (Figure 27) suggests that if the spectrum is folded about the 0.25 cycles per mile frequency (four mile wavelength) aliasing will be within the prescribed limits. On this basis the maximum allowable digital interval for the area was considered to be two miles. All maps and filters were then digitized by taking elevations at uniformly spaced two mile intervals. Elevations were estimated to the nearest ten feet and were obtained by interpolation from nearby wells and contour lines.

The spatial filtering equations are in standard x y z co-ordinates and the same system was used to designate all digital positions in the maps. An overlay with the digital lines insured that each sample position was duplicated on every map. The sampled elevations were punched on I.B.M. cards with each card containing ten elevations and the co-ordinate location of the first sample on the card (FORMAT (4X,10I5,17X,I3, 1X,I3)). The remaining locations ran consecutively from west

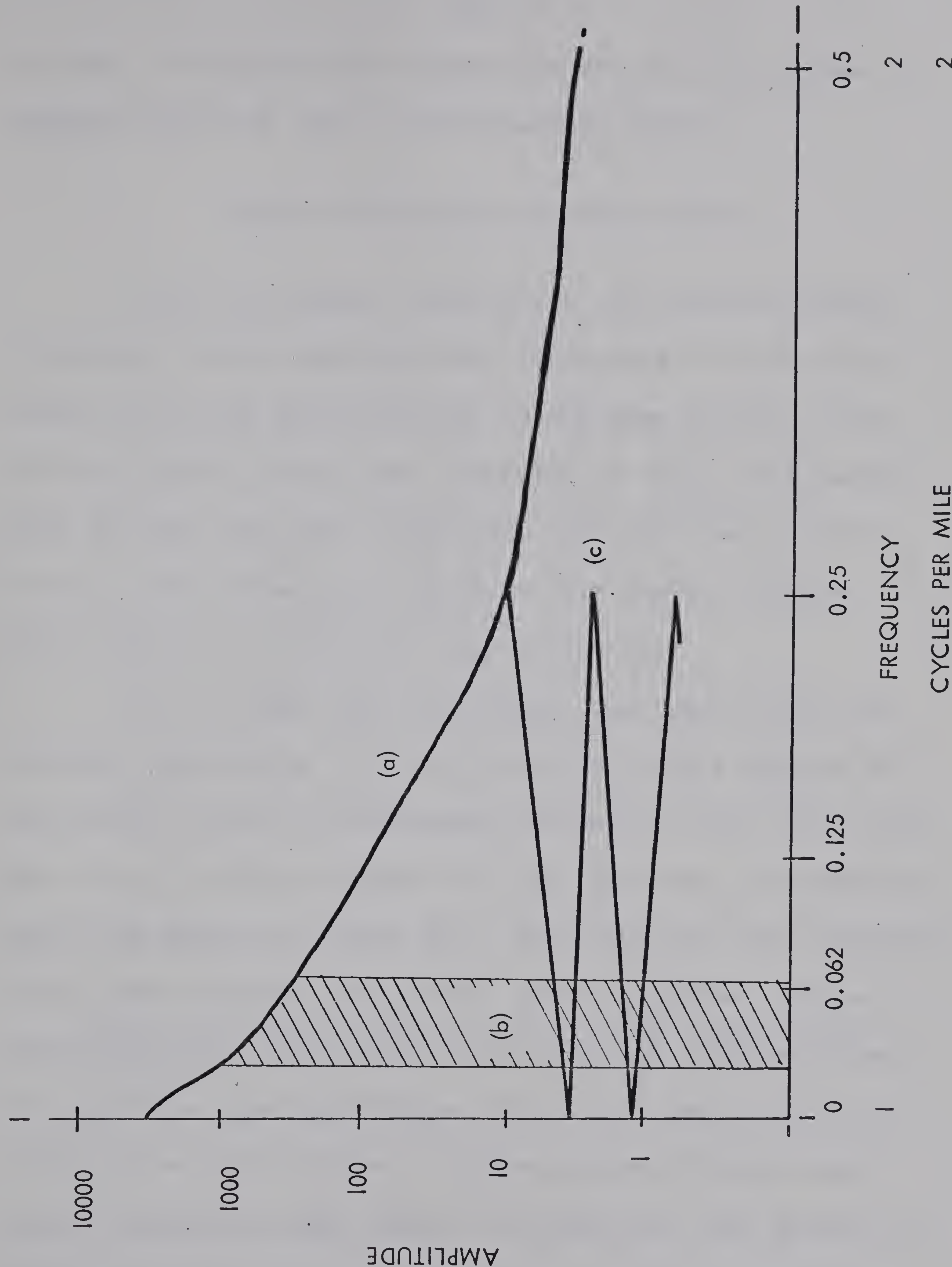

Figure 27

(a) Composite amplitude spectrum for southern Alberta.
(b) is the desirable range of frequencies.
(c) is the amplitude of the aliased frequencies for a digital sample spacing of two miles.

to east. The cards were checked for errors then stacked on magnetic tape for use in the filtering program.

Digital Filters for Southern Alberta

When the digital interval for the southern Alberta structural contour maps had been determined the continuous filter functions were digitized to the same spacing. The initial digital values were corrected so their sum equalled zero for the band pass filters and unity for the regional filter. The result was a suite of five spatial filters that could be convolved with any of the maps.

In its final form the primary band pass filter for southern Alberta was a 13 x 13 matrix of values (Figure 28) that would retain all wavelengths between ten and sixty miles was a 11 x 11 matrix (Figure 30) that also had a satisfactory amplitude spectrum (Figure 31). The third and lower frequency filter that retained wavelengths between eighteen and one hundred and five miles was a 15 x 15 matrix (Figure 32) and its amplitude spectrum (Figure 33) has the least distortion of the three main filters. All the present filters cause only a relatively small amount of distortion that should not concern the direction of digitization or the interpretation. The fourth band pass filter, that was scaled to retain only the relatively narrow range of high frequencies with wave-lengths between six and thirty miles, is a 7 x 7 matrix

-0.011	-0.009	-0.005	0.000	0.000	0.000	0.000
-0.033	-0.030	-0.026	-0.016	-0.006	0.000	0.000
-0.034	-0.036	-0.037	-0.033	-0.019	-0.006	0.000
0.004	-0.004	-0.024	-0.036	-0.033	-0.016	0.000
0.082	0.066	0.014	-0.024	-0.037	-0.026	-0.005
0.170	0.132	0.066	-0.004	-0.036	-0.030	-0.009
0.204	0.170	0.082	0.004	-0.034	-0.033	-0.011

Figure 28

One quadrant of a symmetric 13 x 13 distance domain band pass filter. Digital interval is 2 miles. Wavelengths between 14 and 80 miles are retained.

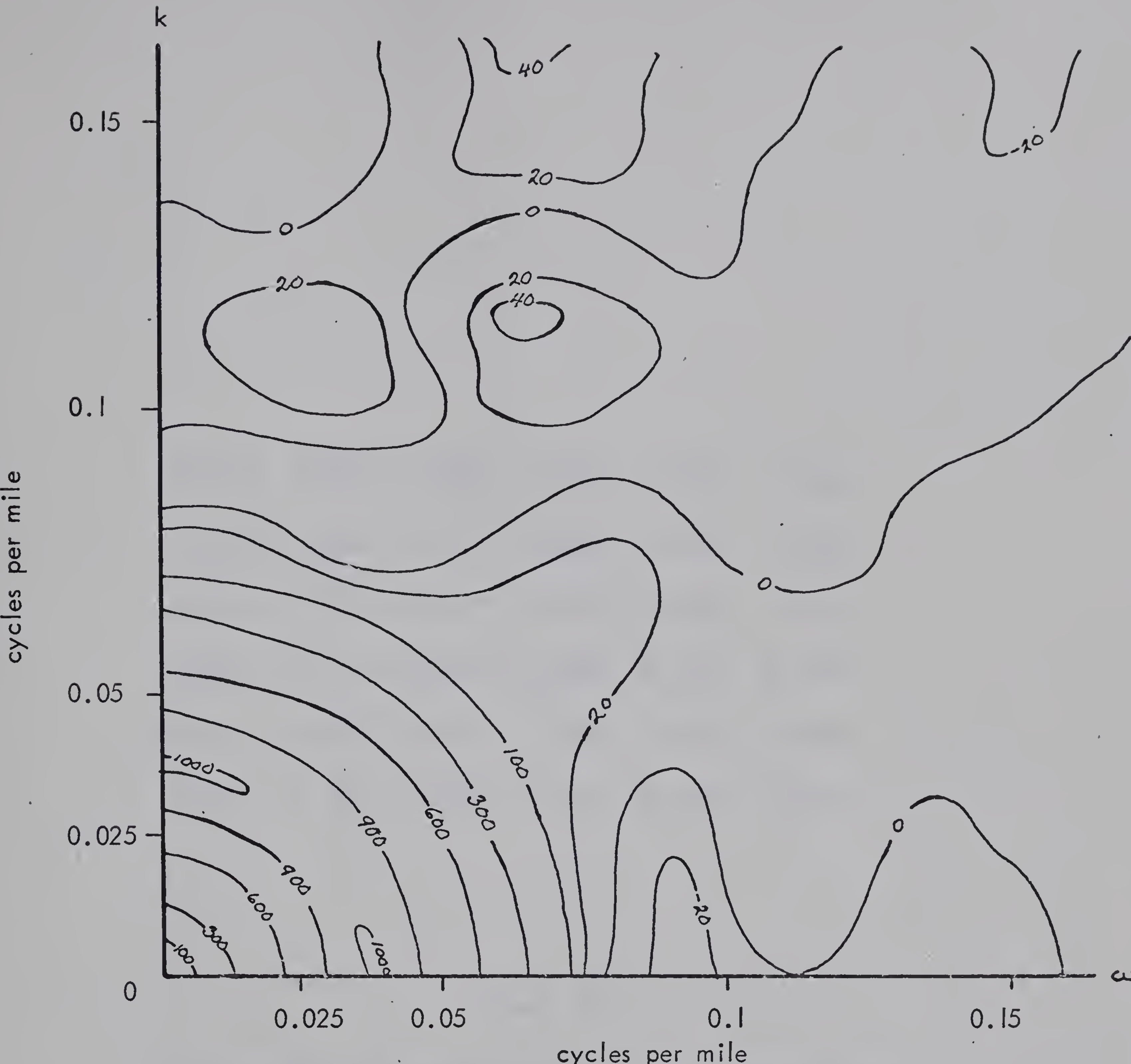

Figure 29

Bilaterally symmetric amplitude spectrum of the 13 x 13 spatial filter.

-0.005	0.000	0.000	0.000	0.000	0.000
-0.022	-0.019	-0.014	-0.005	0.000	0.000
-0.017	-0.022	-0.024	-0.018	-0.005	0.000
0.024	0.011	-0.015	-0.024	-0.014	0.000
0.101	0.067	0.011	-0.022	-0.019	0.000
0.137	0.101	0.024	-0.018	-0.022	-0.005

Figure 30

One quadrant of a symmetric 11 x 11 distance domain band pass filter. Digital interval is 2 miles. Wavelengths between 10 and 60 miles are retained.

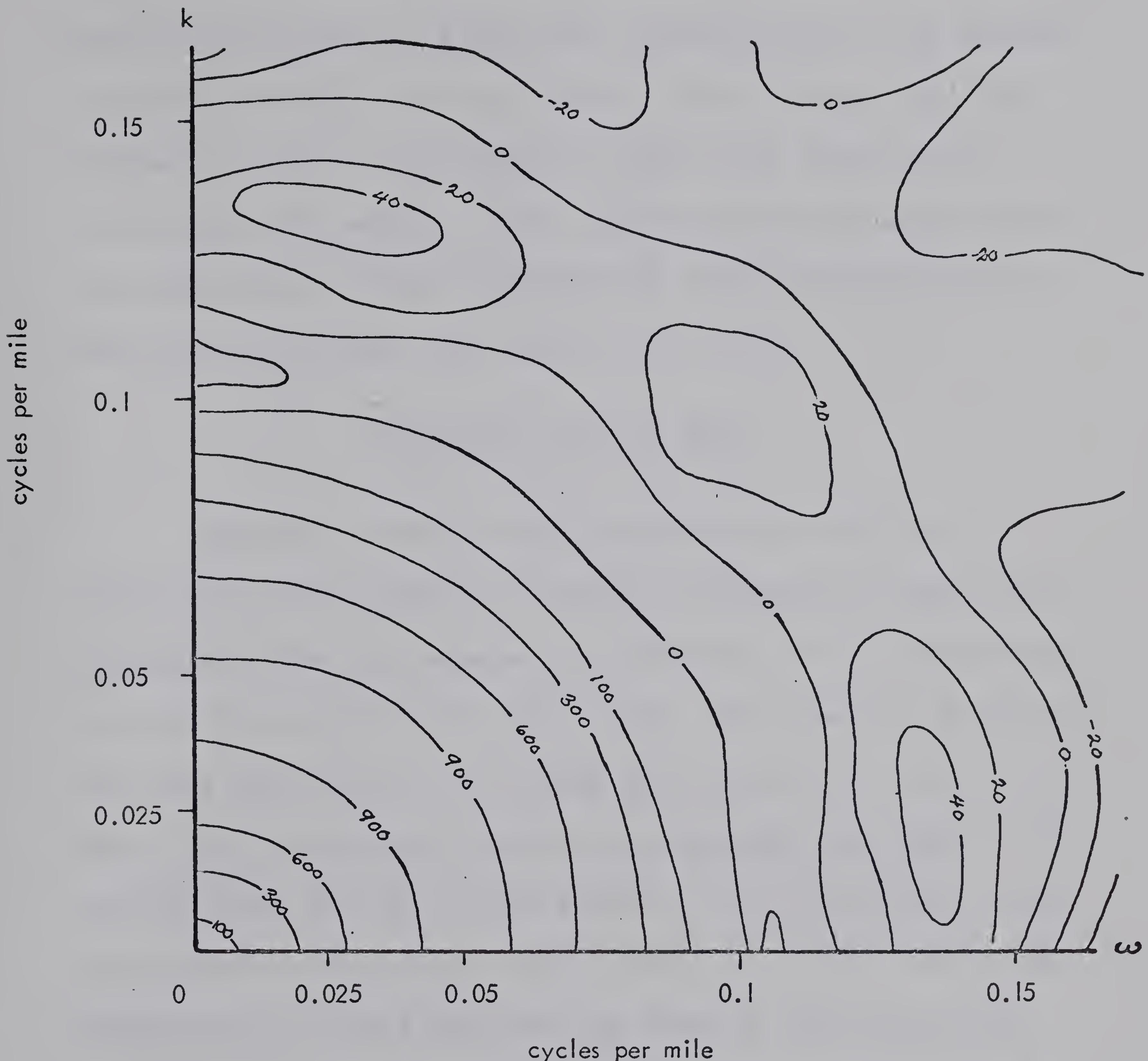

Figure 31

Bilaterally symmetric amplitude spectrum of the 11 x 11 spatial filter.

(Figure 34). This last filter would not be considered suitable for all the maps. It was designed to determine whether or not the short wavelengths at the upper limit of the intermediate scale made any significant contribution to the desired structural trends. The last digital filter (Figure 35) was designed to pass all wavelengths longer than thirty miles and is a 21 x 21 matrix. This regional filter enhances large scale structures and any intermediate scale structures with a width that is greater than twenty five miles.

Processing Digital Maps

Spatially filtered maps were prepared from the digital data using Computer Program 3 (Appendix). The initial outputs were used to compare the efficiency of the filters and to check for errors in the input data. The computer program convolves the filter with the map and outputs the result in a symbolically contoured form that approximates the shape of the original maps and can be used directly for a preliminary study. The extraneous edge area, equal to half the filter width, was automatically deleted from the map edges of the output but there is still some edge effect where the maps indent from the required rectangular matrix.

A correctly designed spatial filter only deletes unwanted structures clearly retaining the desired ones in their

-0.007	-0.006	-0.004	-0.003	0.000	0.000	0.000	0.000
-0.010	-0.009	-0.009	-0.007	-0.005	-0.002	0.000	0.000
-0.009	-0.009	-0.010	-0.010	-0.009	-0.006	-0.002	0.000
-0.001	-0.002	-0.005	-0.009	-0.010	-0.009	-0.005	0.000
0.011	0.009	0.003	-0.004	-0.009	-0.010	-0.007	-0.003
0.033	0.027	0.017	0.003	-0.005	-0.010	-0.009	-0.004
0.049	0.044	0.027	0.009	-0.002	-0.009	-0.009	-0.006
0.054	0.049	0.033	0.011	-0.001	-0.009	-0.010	-0.007

Figure 32

One quadrant of a symmetric 15 x 15 distance domain band pass filter. Digital interval is 2 miles. Wavelengths between 18 and 110 miles are retained.

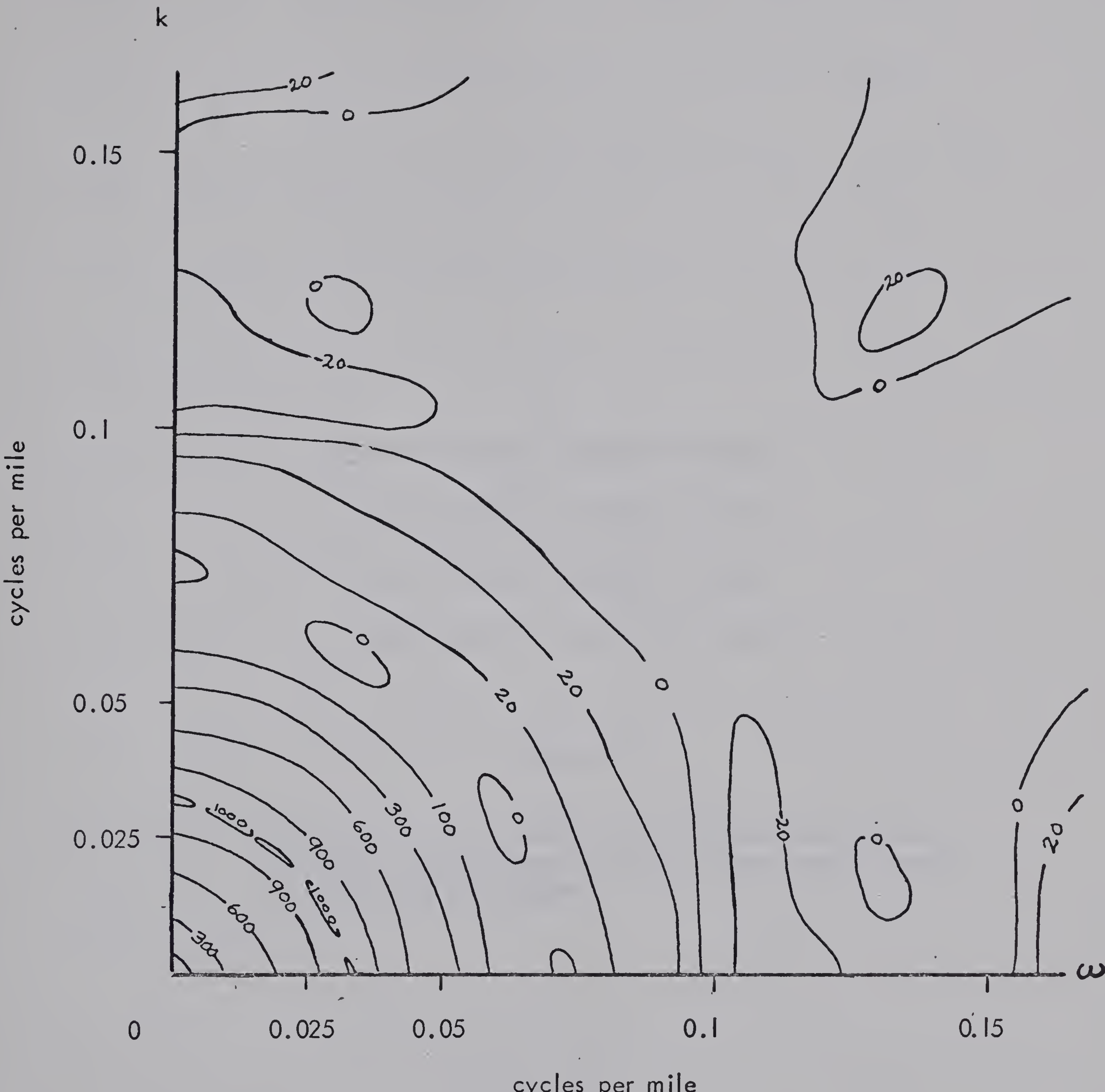

Figure 33

Bilaterally symmetric amplitude spectrum of the 15 x 15 spatial filter.

-0.040	-0.031	-0.014	-0.012
-0.017	-0.031	-0.042	-0.014
0.137	0.053	-0.031	-0.031
0.255	0.137	-0.018	-0.040

Figure 34

One quadrant of a symmetric 7 x 7 distance domain band pass filter. Digital interval is 2 miles. Wavelengths between 6 and 30 miles are retained.

-0.023	-0.023	-0.021	-0.019	-0.015	0.000	0.000	0.000	0.000	0.000	0.000
-0.033	-0.033	-0.031	-0.027	-0.025	-0.022	-0.016	0.000	0.000	0.000	0.000
-0.038	-0.037	-0.036	-0.035	-0.034	-0.028	-0.023	-0.017	0.000	0.000	0.000
-0.036	-0.037	-0.037	-0.038	-0.038	-0.035	-0.031	-0.024	-0.017	0.000	0.000
-0.014	-0.016	-0.021	-0.032	-0.037	-0.038	-0.036	-0.031	-0.023	-0.016	0.000
0.025	0.023	0.008	-0.007	-0.021	-0.036	-0.038	-0.035	-0.028	-0.022	0.000
0.076	0.068	0.036	0.025	0.006	-0.021	-0.037	-0.038	-0.034	-0.025	-0.015
0.124	0.115	0.096	0.066	0.025	-0.007	-0.032	-0.038	-0.035	-0.027	-0.019
0.179	0.164	0.134	0.096	0.036	0.008	0.021	-0.037	-0.036	-0.031	-0.021
0.214	0.204	0.164	0.115	0.068	0.023	-0.016	-0.037	-0.037	-0.033	-0.023
0.228	0.214	0.179	0.124	0.076	0.025	-0.014	-0.036	-0.038	-0.033	-0.023

Figure 35

One quadrant of a symmetric 21 x 21 distance domain regional filter. Digital interval is 2 miles. Wavelengths longer than 30 miles are retained.

original position and shape. The desired structures can be located in the original map although they may be obscured by conflicting structures. Filtered outputs using several spatial filters can be compared and the best filter for any area is the one that most distinctly reproduces the greatest number of the desired structures.

The spatial filters for southern Alberta were evaluated by comparing their effect on the sub-Cretaceous unconformity. The filtered map (Figure 36) from the 13 x 13 band pass filter proved to be the most satisfactory and would be the one used for the structural analysis. The slightly higher pass 11 x 11 filter was nearly as efficient (Figure 37), but the lower pass 15 x 15 filter gave only rather poor definition to the intermediate scale structures and would not be suitable (Figure 38).

The map produced from the 21 x 21 regional filter also contained weakly defined hints of the intermediate trends (Figure 39). The two latter filters confirmed the preliminary interpretation from the composite amplitude spectrum that there is only a negligible contribution to the intermediate scale structures of southern Alberta from any wavelength longer than fifty miles. Intermediate scale structures with a minimum dimension greater than approximately twenty five miles should not be anticipated in this area.

The output from the 7 x 7 high pass filter (Figure 40)

consisted of unrelated, relatively random structures unlike the well defined intermediate trends retained by the 13 x 13 filter. The extra filters confirmed the original filter design with evidence that the important intermediate scale structures of southern Alberta fall into definite structural trends with a minimum dimension ranging from ten to twenty five miles.

A structural analysis requires consistent methods of measurement and the best spatial filter (13 x 13) was used to produce the final suite of maps for the main study. So that the relief on the filtered structures would approximate that of the unfiltered counterparts the filter coefficients were increased by a factor of 2.2 (Figure 41 and 42). This amplification factor was determined from a comparison of a variety of structures in the counterpart maps. Filtered and computer contoured maps were made on the First White Specks (Figure 43), the base of the Fish Scales (Figure 44), the sub-Cretaceous unconformity (Figure 45) and the Devonian top (Figure 46). The isopach subroutine in the mapping program was used to map the differences between the outputs of the filtered surfaces. Since the best spatial filter for the intermediate scale structures is a band pass filter that

-0.005	-0.004	-0.002	0.000	0.000	0.000	0.000
-0.014	-0.013	-0.011	-0.007	-0.003	0.000	0.000
-0.014	-0.015	-0.016	-0.014	-0.008	-0.003	0.000
-0.002	-0.002	-0.010	-0.015	-0.014	-0.007	0.000
0.034	0.028	0.006	-0.010	-0.016	-0.011	-0.002
0.071	0.056	0.028	-0.017	-0.015	-0.013	-0.004
0.086	0.071	0.034	0.002	-0.014	-0.014	-0.005

Figure 41

One quadrant of a symmetric 13 x 13 distance domain band pass filter. Digital interval is 2 miles. Wavelengths between 14 and 80 miles are retained. Gain is 2.2.

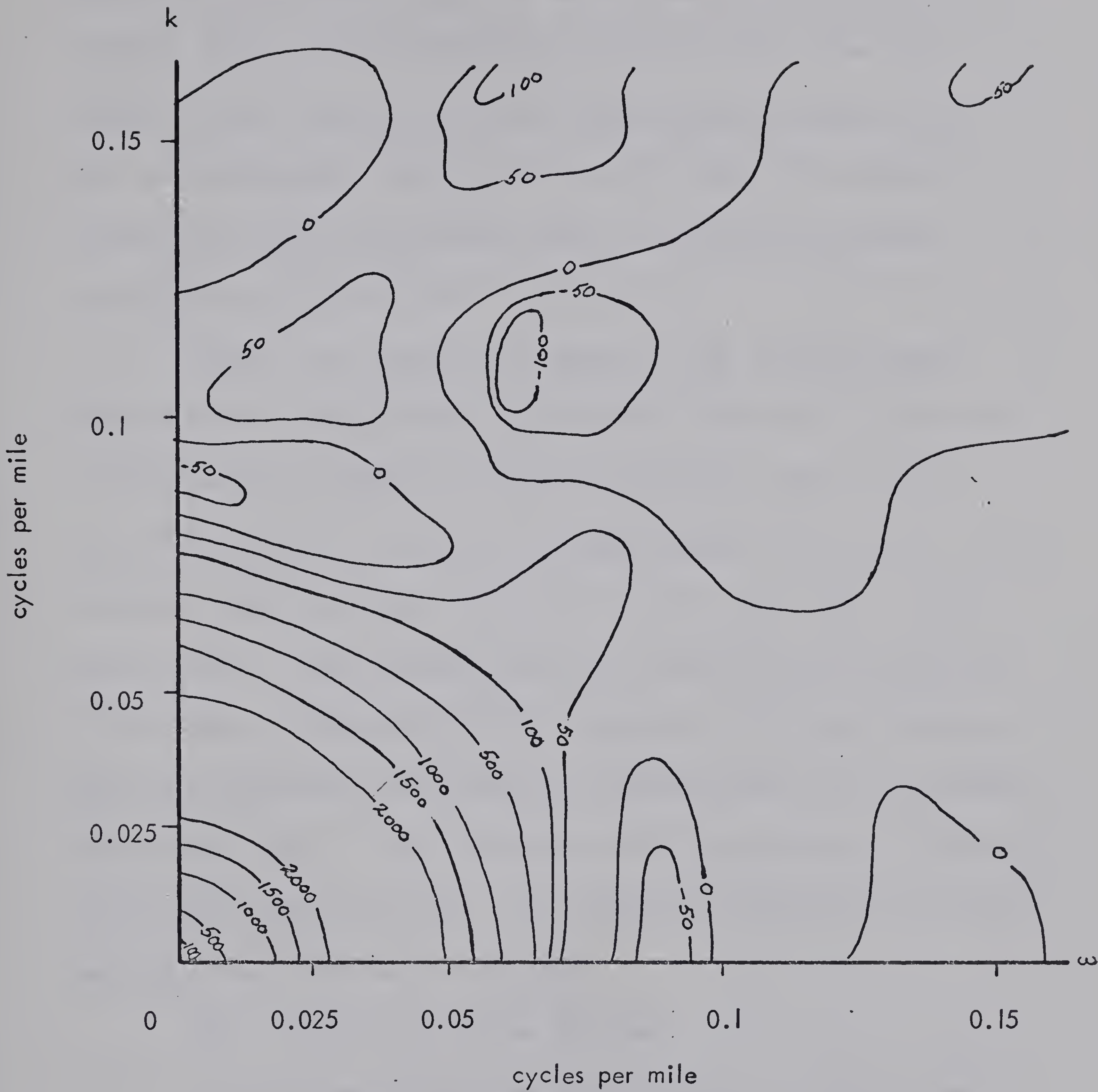

Figure 42

Bilaterally symmetric amplitude spectrum
of the 13 x 13 spatial filter

2.2 gain

deletes the average elevation, the latter outputs are apostreptic maps where positive anomalies are equivalent to isopach thins. The apostreptic maps span the base Fish Scales to the top of the First White Specks (Figure 47), the sub-Cretaceous unconformity to the base Fish Scales (Figure 48) and the Devonian top to the sub-Cretaceous unconformity (Figure 49).

After the computer outputs of the filtered maps were examined and checked for errors, the spread subroutine in the mapping program was used to produce symbolically contoured maps on a scale that approximated the scale of the original maps as closely as the computer carriage control would allow. The computer maps were mechanically adjusted to the exact dimensions of the original structural contour maps, re-contoured onto overlays and printed with a standard topographic base. This produced the final suite of filtered, structural contoured maps and apostreptic maps that would be used for the structural analysis.

The final maps are as follows:

a) Filtered structure contours on the top of the First White Specks (Figure 50)

b) Filtered structure contours on the base of the Fish Scales (Figure 51).

c) Filtered structure contours on the sub-Cretaceous unconformity (Figure 52).

d) Filtered structure contours on the Devonian top (Figure 53).

e) Apostreptic map between the base of the Fish Scales and the top of the First White Specks (Figure 54).

f) Apostreptic map between the sub-Cretaceous unconformity and the base of the Fish Scales (Figure 55).

g) Apostreptic map between the Devonian top and the sub-Cretaceous unconformity (Figure 56).

Errors in Digital Maps

All mapping and data handling procedures generate some error. There is a degree of error inherent in the original information that can only be tolerated and allowed for in the contouring interval. However, many of the errors that subsequently appear in the data are mechanical mistakes that can and should be corrected.

If it can be assumed that the original group of structural contour maps have been checked repeatedly until their accuracy is within the limits of the available well control, they can be used as a standard to evaluate errors generated in the later processing. These errors occur during

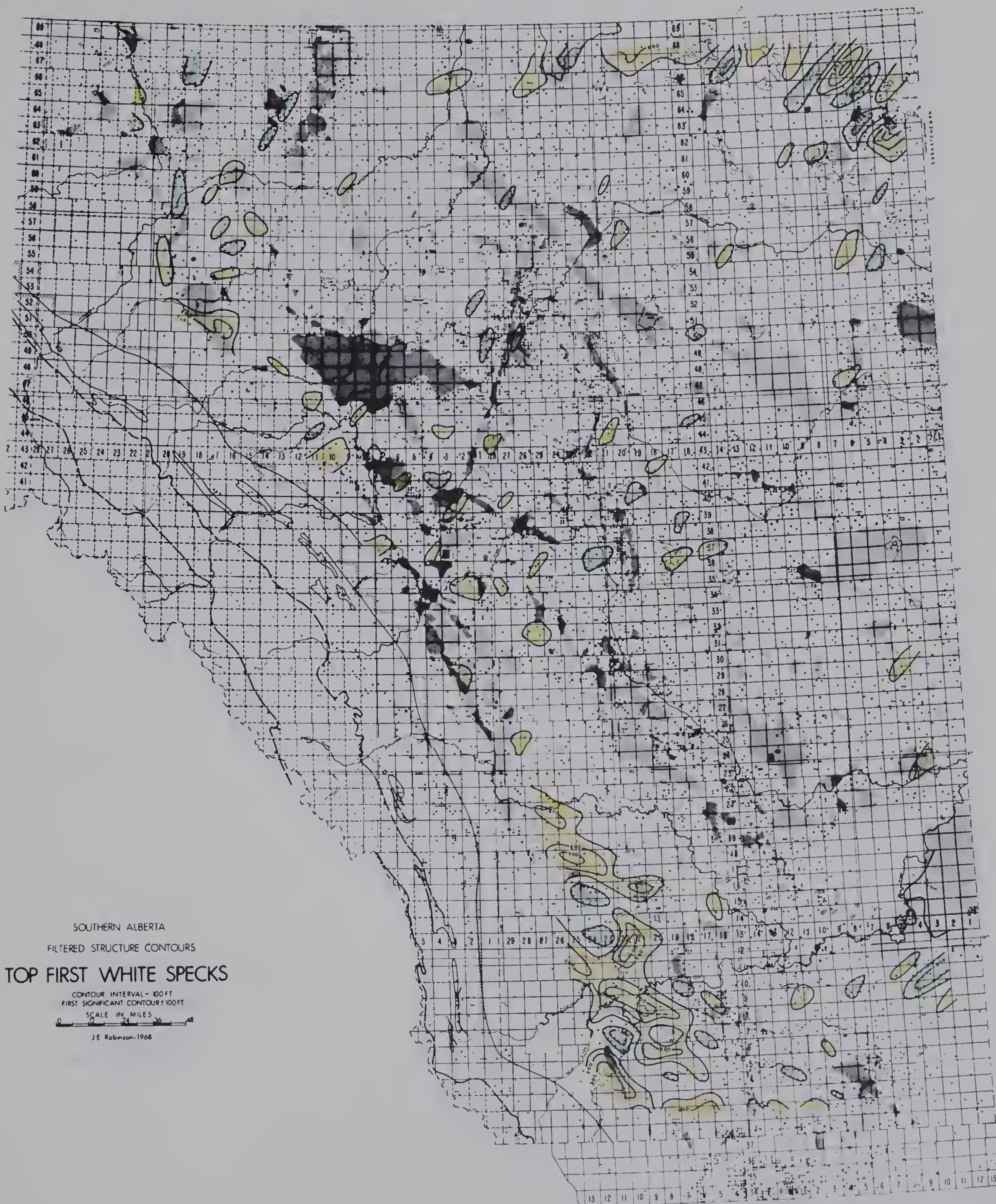
SOUTHERN ALBERTA
FILTERED STRUCTURE CONTOURS
TOP FIRST WHITE SPECKS
CONTOUR INTERVAL - 100 FT
FIRST SIGNIFICANT CONTOUR ± 100 FT
SCALE IN MILES
0 12 24 36 48
J E Robinson - 1968

Figure 50

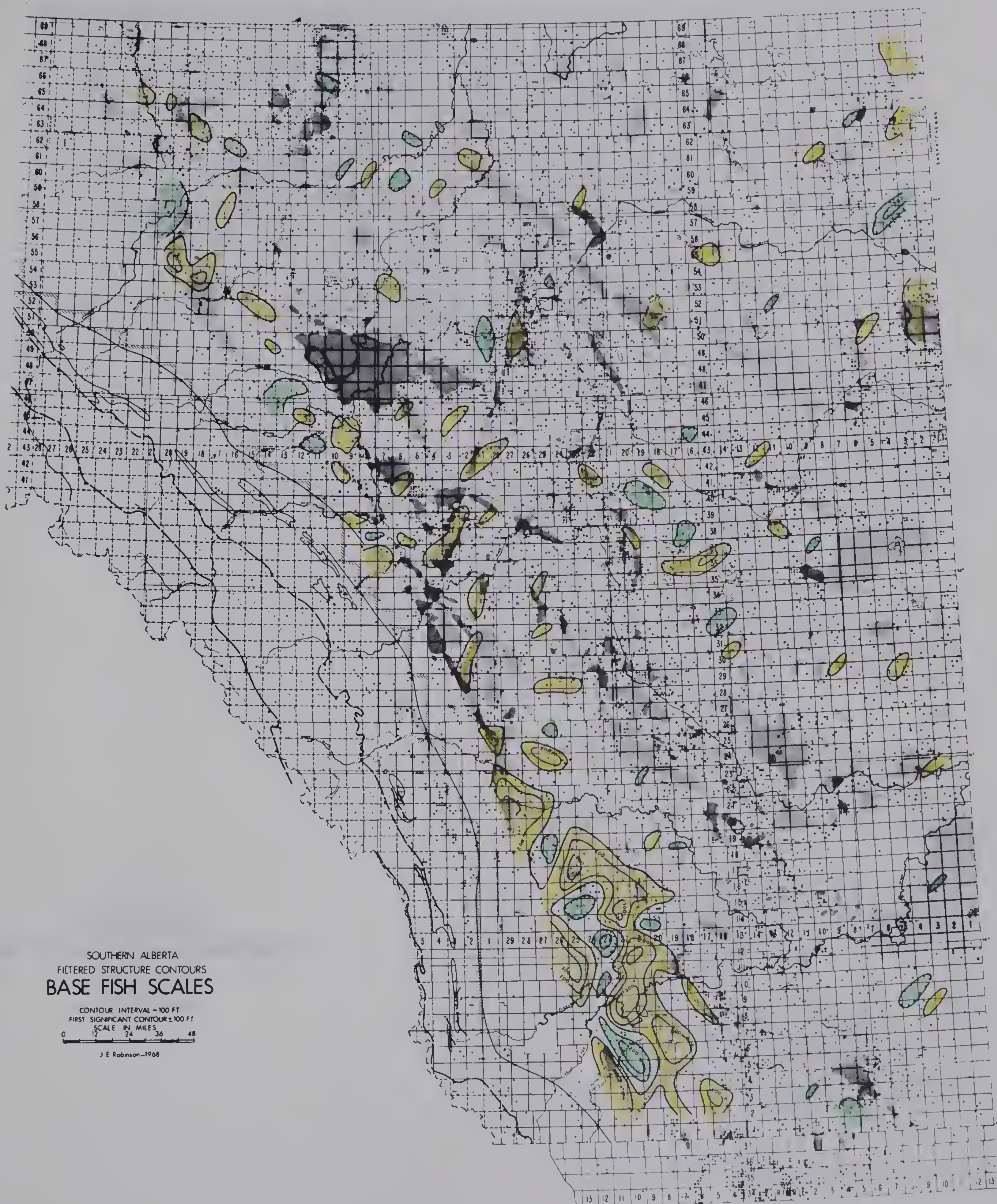
SOUTHERN ALBERTA
FILTERED STRUCTURE CONTOURS
BASE FISH SCALES
CONTOUR INTERVAL – 100 FT
FIRST SIGNIFICANT CONTOUR ± 100 FT
SCALE IN MILES
0 12 24 36 48
J E Robinson – 1968

Figure 51

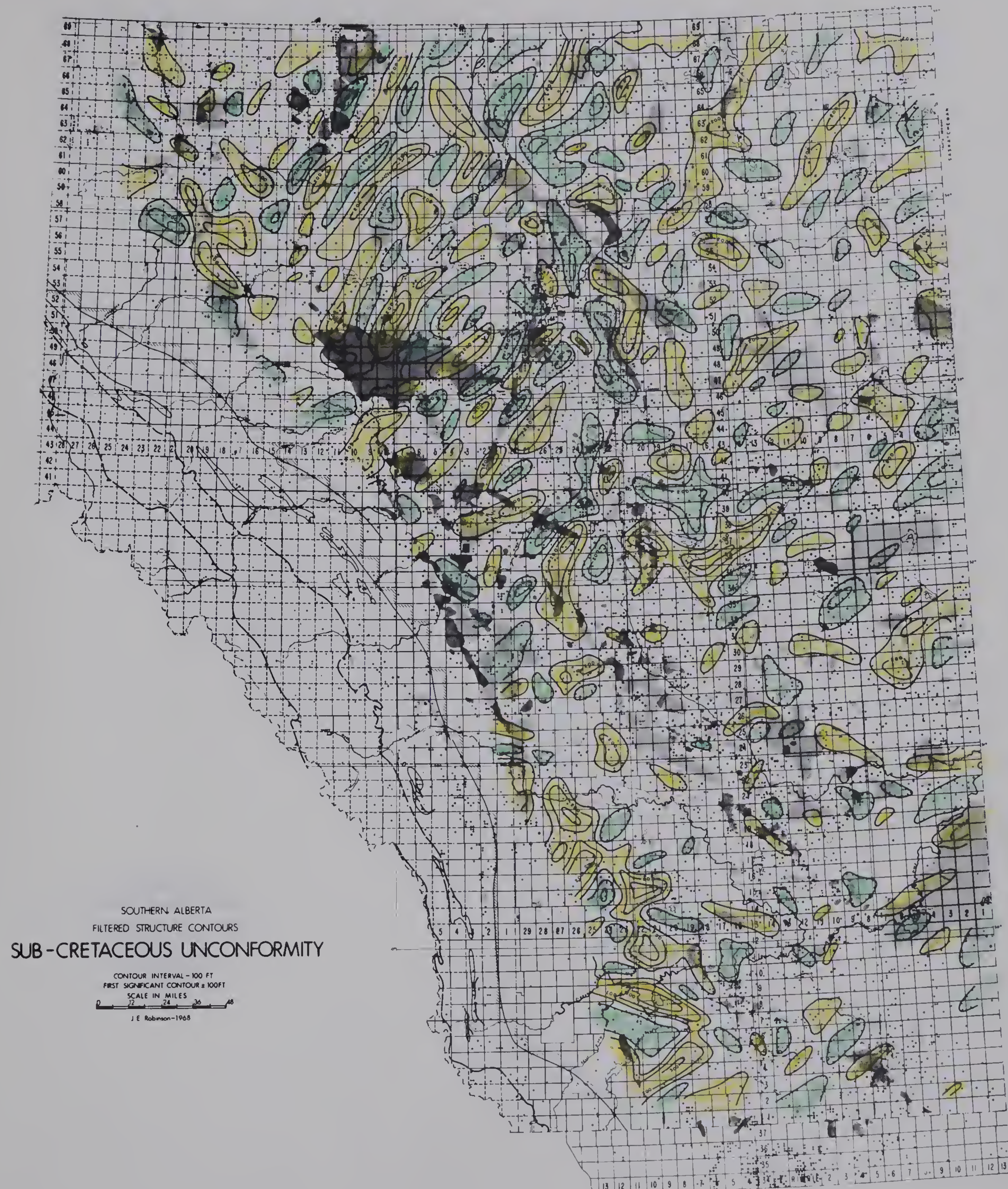
SOUTHERN ALBERTA
FILTERED STRUCTURE CONTOURS
SUB-CRETACEOUS UNCONFORMITY
CONTOUR INTERVAL - 100 FT
FIRST SIGNIFICANT CONTOUR ± 100FT
SCALE IN MILES
0 12 24 36 48
J E Robinson-1968

Figure 52

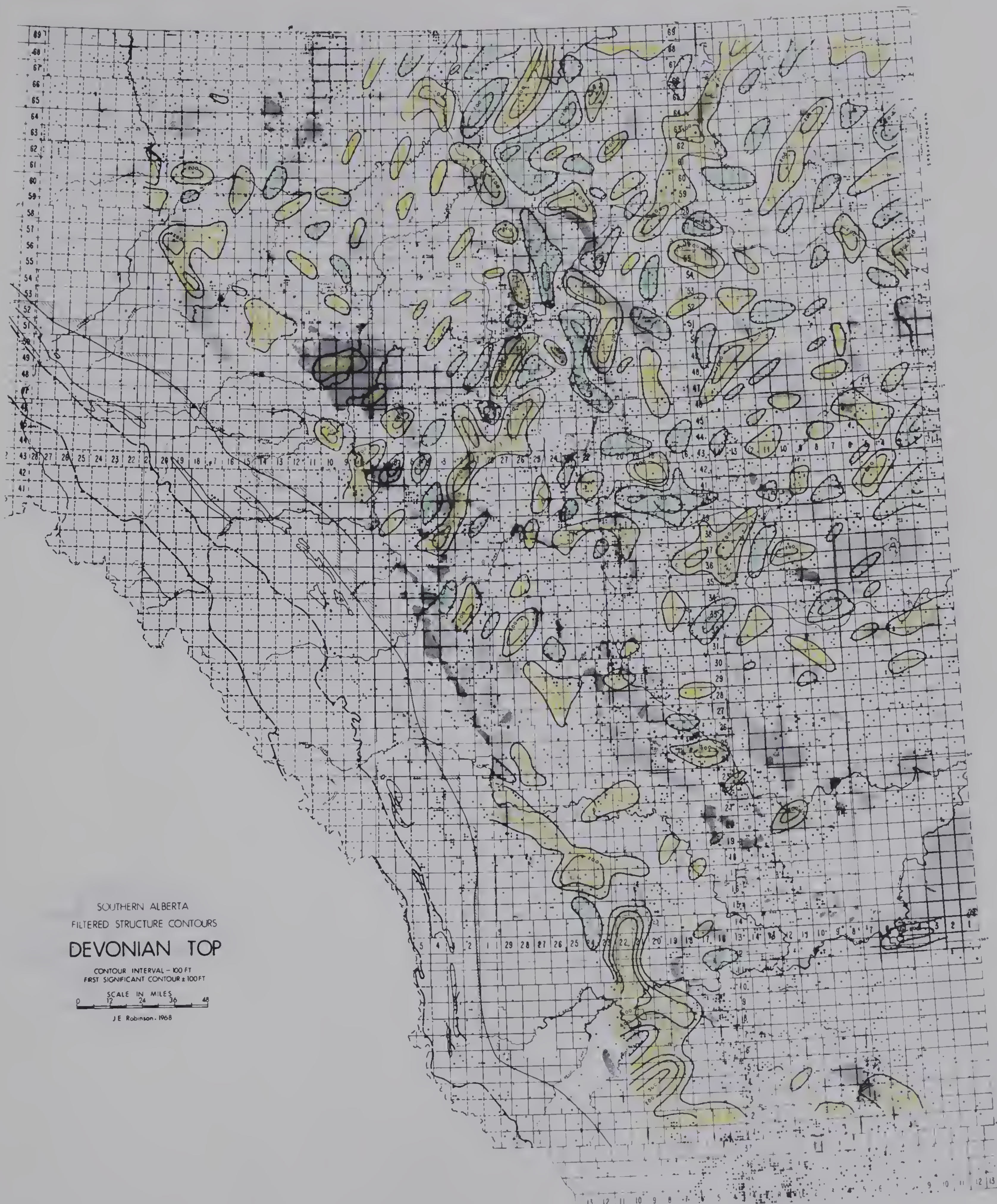
SOUTHERN ALBERTA
FILTERED STRUCTURE CONTOURS
DEVONIAN TOP
CONTOUR INTERVAL - 100 FT
FIRST SIGNIFICANT CONTOUR ± 100 FT
SCALE IN MILES
0 12 24 36 48
J E Robinson - 1968

Figure 53

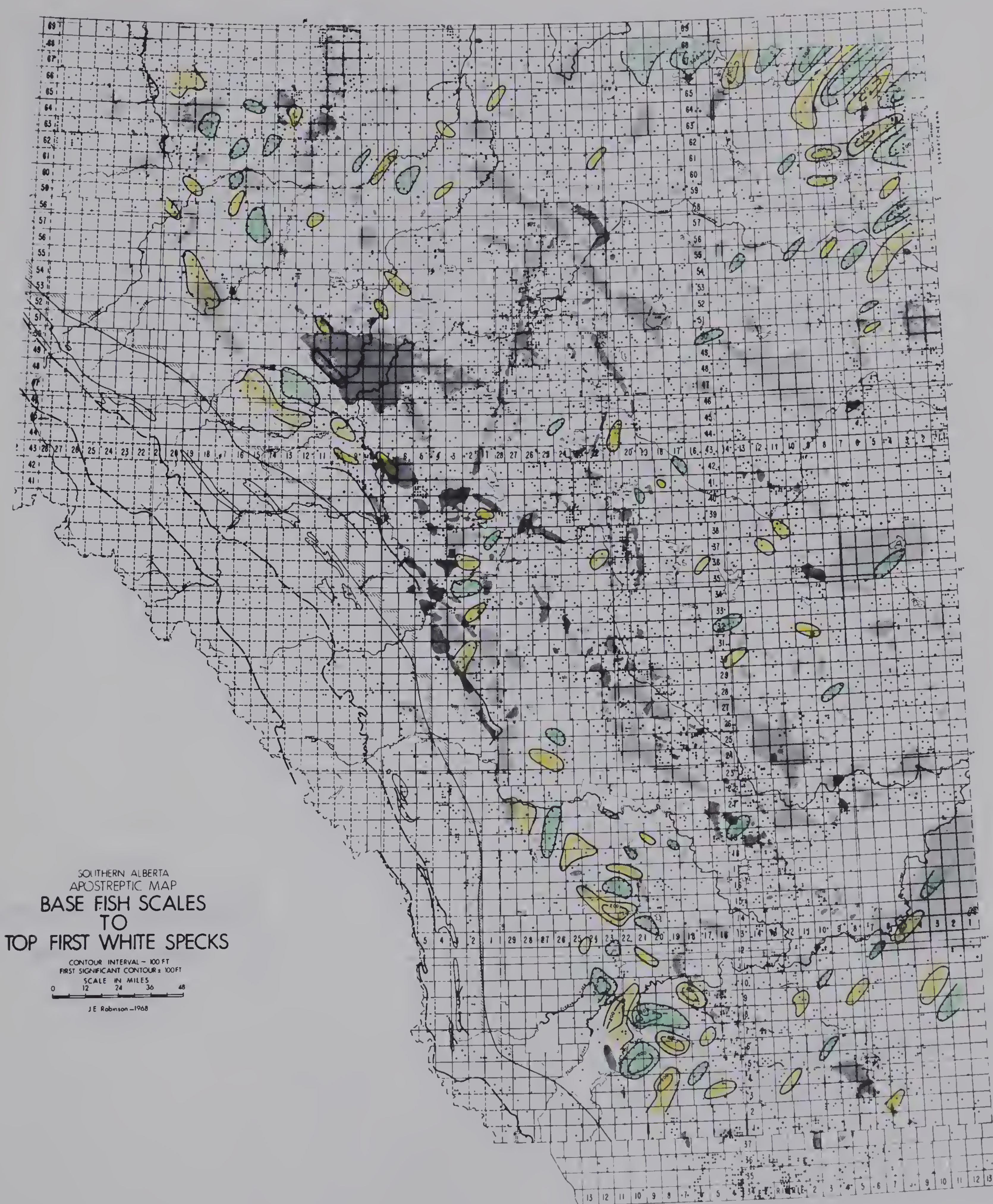
SOUTHERN ALBERTA
APOSTREPTIC MAP
BASE FISH SCALES
TO
TOP FIRST WHITE SPECKS
CONTOUR INTERVAL – 100 FT
FIRST SIGNIFICANT CONTOUR ± 100 FT
SCALE IN MILES
0 12 24 36 48
J E Robinson – 1968

Figure 54

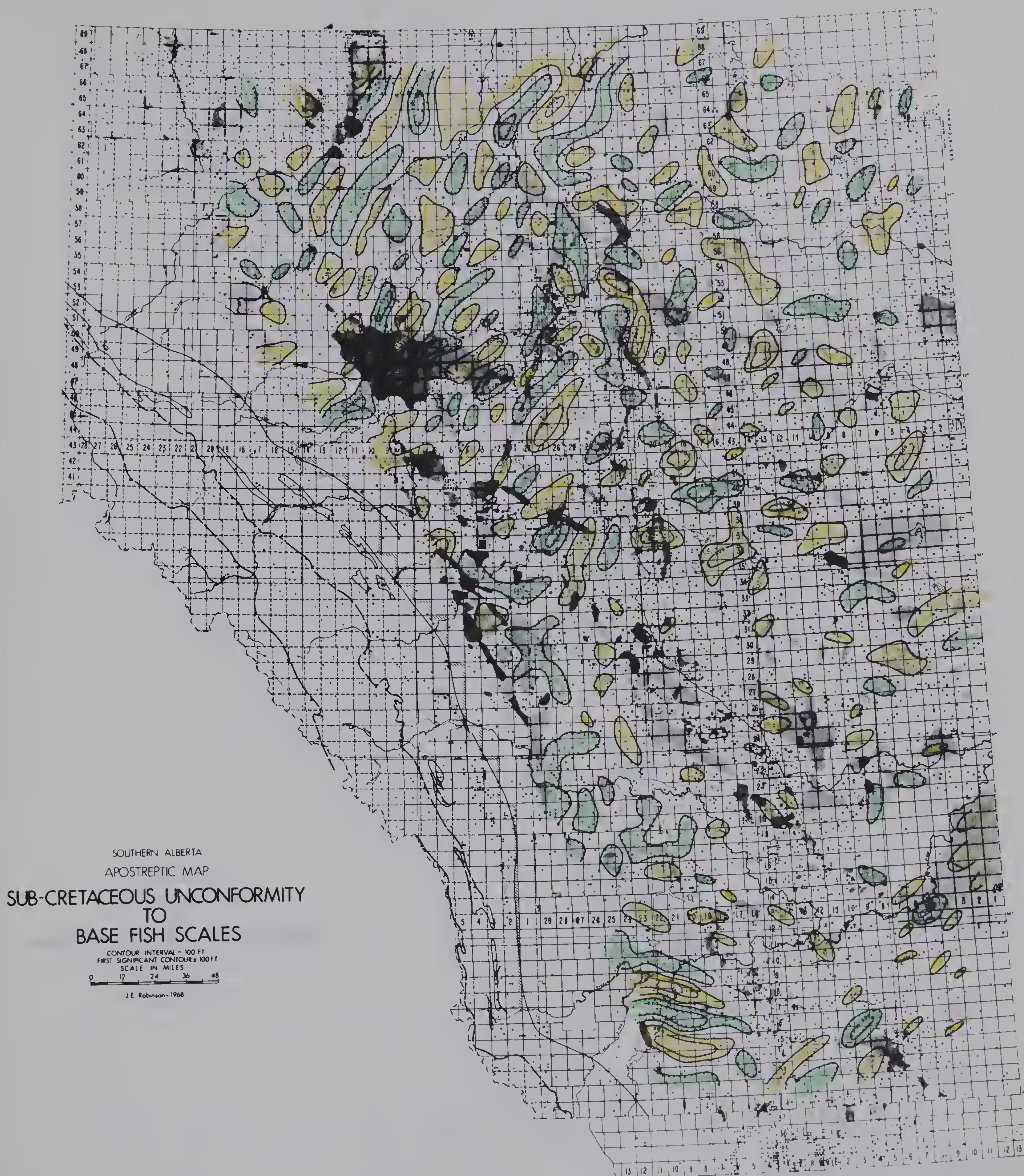
SOUTHERN ALBERTA
APOSTREPTIC MAP
SUB-CRETACEOUS UNCONFORMITY
TO
BASE FISH SCALES
CONTOUR INTERVAL – 100 FT
FIRST SIGNIFICANT CONTOUR ± 100 FT
SCALE IN MILES
0 12 24 36 48
J E Robinson – 1968

Figure 55

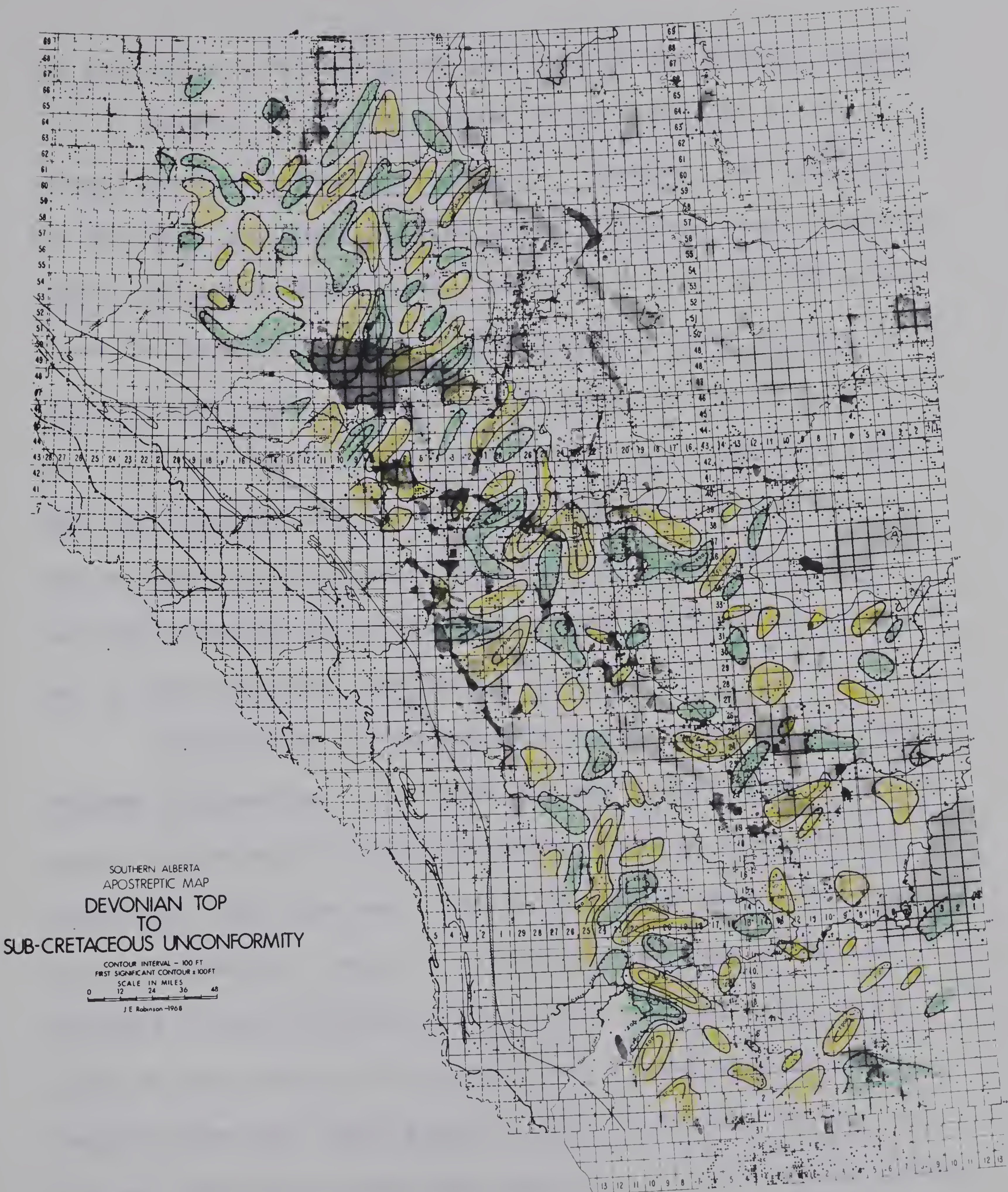
SOUTHERN ALBERTA
APOSTREPTIC MAP
DEVONIAN TOP
TO
SUB-CRETACEOUS UNCONFORMITY
CONTOUR INTERVAL – 100 FT
FIRST SIGNIFICANT CONTOUR ± 100 FT
SCALE IN MILES
0 12 24 36 48
J E Robinson –1968

Figure 56

the estimation, recording and punching of the digital values.

Spatial filters are small in area and can be rigorously checked by hand calculation. However, map surfaces may be large and their digital description may require several hundred thousand data values. There were over 150,000 elevations for southern Alberta. When a large volume of data is involved inevitably a considerable number of errors slip past the preliminary checks and appear on the magnetic tape used for computer input. The vast majority of these errors can be found by a careful examination of the filtered output and corrected before the final maps are produced for use in the structural analysis.

Corrections to the magnetic tape are made with Computer Program 4 (Appendix). If there are any illegal characters or cards the convolution program simply stops at the point of interrupt. The data must then be corrected before the map can be completed. Legal but wrong values cause anamalous features in the filtered output. Each digital value is reduced by the convolution process to a finite band of wavelengths whose sum looks exactly like the digital filter, so that an individual value error produces a filter shaped anomaly. A line or card of wrong values comes out as an elongate filter shaped feature parallel with the direction of digitization.

Systematic errors are more difficult to find. However, spatial filtering only deletes structures and does not add new ones, so anomalies in the output may be located in the original maps. Unlocatable anomalies are the result of errors and should be corrected or deleted from the interpretation.

Significant data errors should be discovered and deleted until any remaining are so small that their effect is within the limits of accuracy of the original maps. The correction process is tedious but necessary. Fortunately, data gathering systems are becoming more sophisticated so that most of the human error will be elimiated through the use of mechanical digitizers and plotters.

Convolution of a spatial filter with a map reduces the effect of random errors by more than two thirds of their value. Systematic errors may be passed unchanged into the filtered maps but they are usually reduced. Errors are never increased. Consequently, the level of significance of an anomaly in a spatially filtered map is at least the same as in the original maps. The structures in the filtered maps of southern Alberta should be reliable at the fity foot contour level and they are definitely reliable at the one hundred foot contour level used in the final maps.

CHAPTER 4 - GENERAL STRUCTURES IN SOUTHERN ALBERTA

The original structural contour maps exhibit a variety of structures, ranging from the large regional features such as the Sweet Grass Arch in the south, to the high relief small scale structures in the Cypress Hills area. Many of these and other known and inferred structures in southern Alberta do not appear in the filtered maps. They either do not fall within the intermediate scale size range, do not affect the available structural surfaces, or are too subtle for delineation by the present mapping methods (e.g. some of the trends in Figure 57).

The structural contours on the top of the Elk Point (Figure 7) are based on widely spaced well control and the map shows only the large scale structures. These include the strong westerly regional gradient, the Sweet Grass Arch and the North Battleford Arch (Burwash, et. al., 1964). There is also a hint of a E-W trending low through the Vulvan-Brooks area corresponding to the general location of a proposed Precambrian rift valley (Kanasewich, 1967). Known Middle Devonian structures that are likely of intermediate scale, such as the Meadow Lake Escarpment and reefal carbonate banks, are not discernible in the map.

The Devonian top (Figure 6) has more well control and

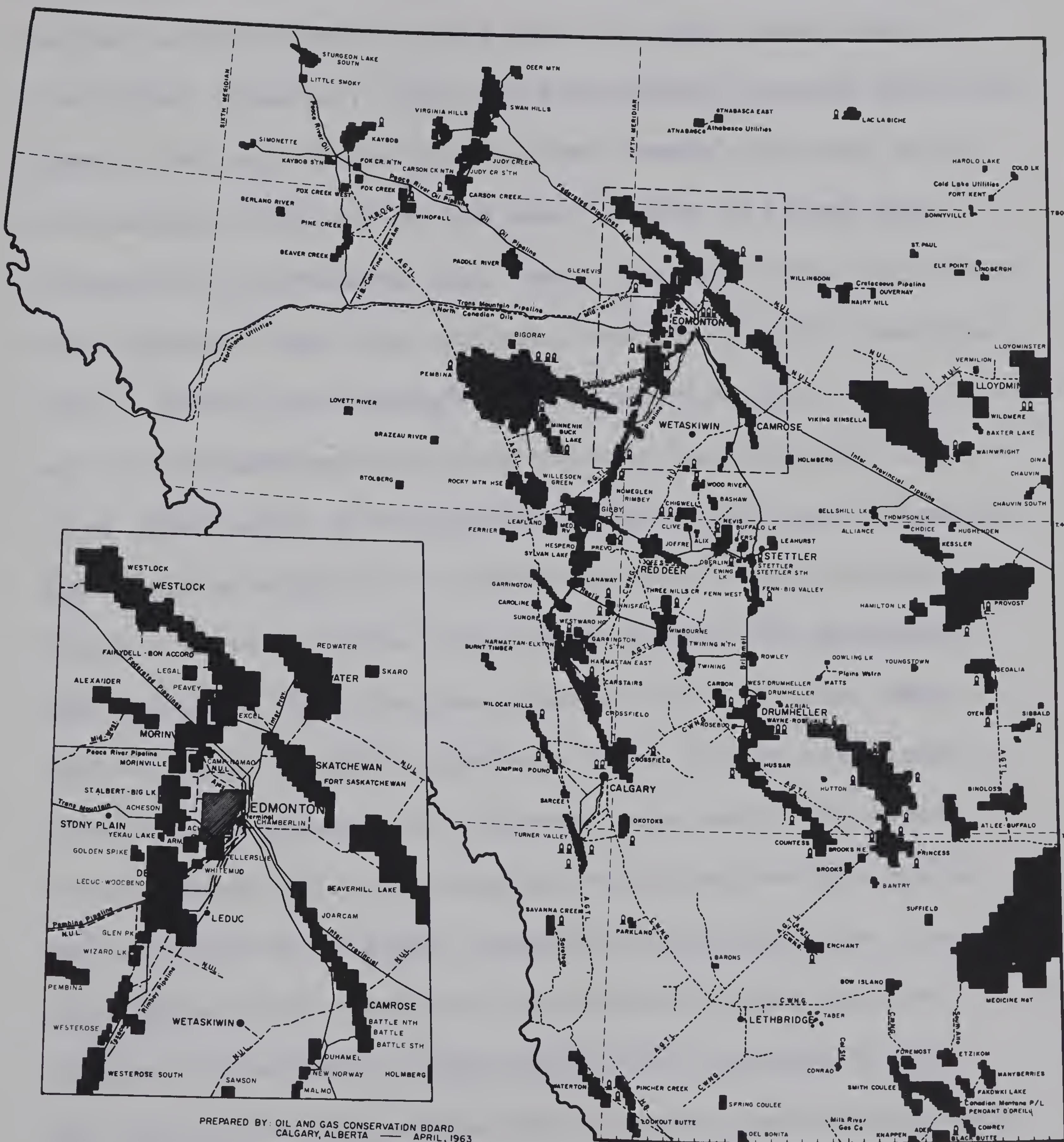

Figure 57

Oil and gas fields of Southern Alberta

can be filtered to enhance the intermediate scale structures. The large scale features are similar to those on the Elk Point surface and are removed along with the small scale ones by the filter. However, there are known Upper Devonian structures (namely the many Upper Devonian reef trends) that may be of intermediate scale and do not seem to show in either the original or the filtered map. Reefs are structures and it has been suggested that they may have tectonic control (Andrichuk, 1961). There is not enough well information for a satisfactory map on the platforms that form the reef base but the oil producing upper parts of the bioherms often have linear alignments that would be expected to follow the controlling tectonic trends. There is a good coincidence between the Beaverhill Lake reefs and the structural trends in the filtered maps (Belyea, et al., 1964). However, there is only occasional co-ordination between the Woodbend reefs and the filtered trends (Figure 57). The original structural contour map on the Devonian top does show compaction structures over the Leduc-Rimbey reef trend but they are small scale and are deleted by the filter. Andrichuck (1961) proposed a tectonic control for many of the reefs but the present study does not have sufficient information for a valid conclusion.

There is better coincidence between the oil and gas confining trends and the map on the sub-Cretaceous un-

conformity. However, it cannot all be attributed to intermediate scale structural control. Some fields, such as those in the Harmatton-Westward Ho, Mississippian subcrop area, are associated with the large scale westerly regional gradient. The oil and gas confining erosional ridges or cuestas and their overlying compaction structures are usually small scale but do parallel the NW-SE intermediate scale trends. The Joffre field does not appear to coincide with structures in any of the maps and has marked divergence from any of the known trends. In contrast, the Westlock-Fairydell gas trend aligns exactly with a NW-SE linear trend and there is little doubt of the close relationship between the fields and the structures. The Cretaceous structural contour map also shows small scale relief over both the Leduc-Rimbey and the Fenn-Big Valley-Stettler reef trends that is not seen in the filtered map.

The structural contour maps on the Base Fish Scales and the First White Specks show small scale structural relief over the prominent Woodbend and Winterburn reef trends and there are also small scale structures in the Cypress Hills and Sweet Grass Arch areas. The most prominent intermediate scale structures are in the SW corner of Alberta and where the First White Specks outcrops in the NW corner. Both maps contain the main large scale structures and numerous small scale ones but relatively few prominent intermediate scale

structures.

The filtered maps retain only those structures that are defined by the available information and are of a scale passed by the filter. All other structures are deleted. The present set of filtered maps actually show only a few of the known and surmised structures of the interior plains of southern Alberta. However, the structures in the filtered maps are valid and can be described and used as the basis for a relatively comprehensive structural analysis.

CHAPTER 5 - STRUCTURAL ANALYSIS

Introduction

A structural analysis involves two philosophically distinct procedures (Turner and Weiss, 1963, p. 7). The first concerns the physical description of the geometry of a rock body and the second attempts to reconstruct the structural evolution of the body. A geometric analysis of a structural contour map or a set of maps, using spatial filtering, can be separated into rigorous and interpretative parts. The rigorous part can be defined mathematically within the confines of the available information whereas the interpretative part includes geological induction.

The line of demarcation between the two parts of the geometric analysis depends on the nature of the available information on the surface or surfaces. If the surface is a stratigraphic horizon in a finite map area, the distinction between the rigorous and the interpretative parts is a function of the sample spacing. In the case of the structural contour maps of southern Alberta, it is a function of the well spacing.

The greatest amount of rigorous information that can be determined from a spatially filtered structural contour map is directly related to the average uniform distance between wells. The information may be quite limited. Gradients in the filtered maps should never exceed the elevation change

between sample locations. Abrupt features such as faults must be interpretative unless there is almost continuous sample coverage. The sample spacing in southern Alberta is only sufficient for the intermediate scale structures to appear as a series of smooth upwarps and downwarps.

The filtered structural contour maps of southern Alberta illustrate the intermediate scale structures within the 50 foot possible error of the original maps. The 100 foot contour level of significance means the features in the filtered maps are valid. Within the designated margin of error, they are rigorous in their width, length, separation and trend. They are not rigorous in their slopes, skewness or absolute shape.

A description of the genetic evolution of the structures contained in a rock body also consists of two parts: a kinematic analysis that attempts to reconstruct the movements that affected the rock body and a dynamic analysis that determines the stress patterns and forces causing the movements. This second procedural part of the structural analysis is inherently interpretative.

Rigorous Geometric Analysis of the Filtered Maps

The filtered structural contour maps (Figures 50 to 53

inclusive) graphically display all significant intermediate scale structural features in two dimensions. The apostreptic maps (Figures 54 to 56) picture the changes in the interval between successive horizons and form a bridge relating the two-dimensional and three-dimensional descriptions.

The Interior Plains of Southern Alberta contain, with minor variations, two main intermediate scale structural trends. The individual structures are linear and trend either NE-SW or NW-SE. The main trend directions are discernible on all areas of the filtered maps but tend to be more uniform in the north than in the south. These linear orthogonal structural trends dominate the filtered structural maps and determine the texture or fabric of the surfaces.

Although the trend of the linear structures is relatively consistent, there is a marked variation in relief from area to area. Within each area the structural amplitudes are relatively consistent permitting the maps to be divided into domains on a basis of uniform relief. The upper surfaces have less relief than the lower permitting the filtered maps to be grouped into two domains, one below (1) and one above (2) the sub-Cretaceous unconformity. Each domain can be divided into three subdivisions (a,b,c) within which the structural amplitude is relatively uniform (Figure 58).

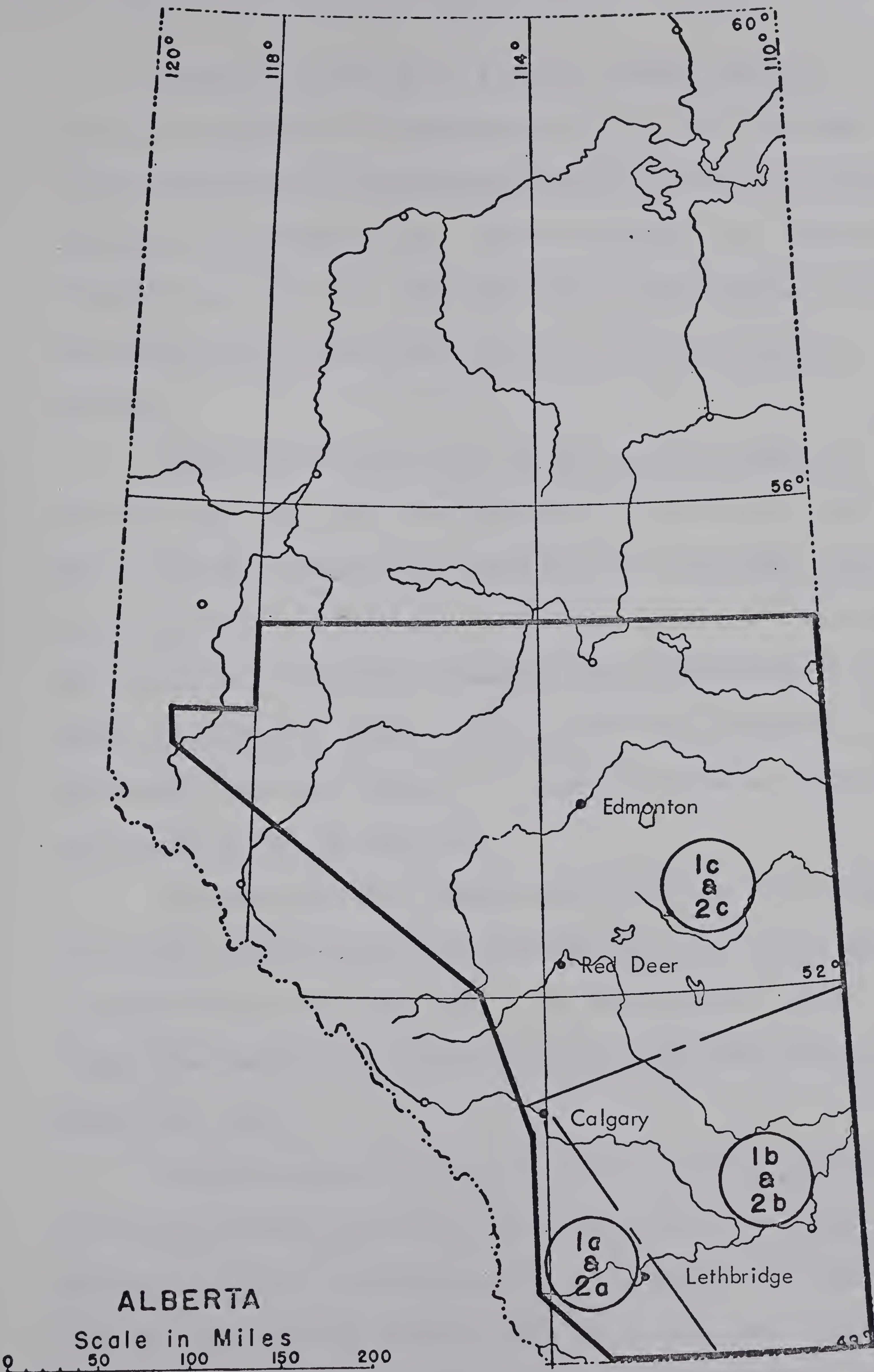

Figure 58

Subdivisions of structural domains in Alberta

Domain (1) made up of surfaces formed prior to Cretaceous deposition is represented by the filtered maps on the Devonian top, the sub-Cretaceous unconformity and the intervening apostreptic map. It is divisable into three subdivisions (1a, 1b, 1c). The positions of the boundaries of the domain subdivisions are subjective but the areas are distinct.

Domain subdivision 1a, the SW corner of Alberta, contains high amplitude structures with relief up to 500 feet. The NE-SW structural trend is by far the most prominent on the Devonian but both main trends are apparent. However, the unconformity exhibits a smaller scale approximately E-W trend that does not appear on any of the other surfaces. The apostreptic map shows there is a marked difference in the structures on the two surfaces.

The structures in domain subdivision 1b, the SE part of Alberta, are of relatively low amplitude and seldom attain a relief of more than 200 feet. The NE-SW and the NW-SE trends are dominate but there are a few structures with an almost E-W trend.

Domain subdivision 1c, in central Alberta, contains pronounced linear structural trends up to 90 miles long. Average relief of structures on the unconformity is less than 400 feet but may locally range up to 500 feet. Relief on the western or depositional portion of the Devonian surface

averages approximately half of that on the unconformity but there are structures with relatively high relief in the area between Edmonton and Red Deer. The apostreptic map indicates that the structures on the Devonian coincide in all except relief with those on the sub-Cretaceous unconformity. The structures on both surfaces predominately trend NE-SW. However, a usually subordinate NW-SE pattern contains one strong linear structure that completely disrupts the continuity of the other trend. This latter structure can be traced continuously for over 100 miles and not only causes a complete break in the NE-SW trend but offsets it so that downwarps appear to be in alignment with upwarps. The geological significance is interpretative and is covered in the next part of the geometric analysis.

The upper domain (2), made up of surfaces formed after the beginning of Cretaceous deposition, is also represented by the filtered structural contour map on the sub-Cretaceous unconformity as well as the maps on the Base Fish Scales, the First White Specks and the intervening apostreptic maps. It is divided into three subdivisions similar to those of domain (1) (Figure 58).

Relief in domain subdivision 2a is relatively high, often reaching more than 500 feet. Structural trends are dominately NW-SE. The NE-SW trend of the underlying subdomain is no longer significant and the approximately East-

West trend that is prominently displayed on the unconformity surface does not appear on the higher surfaces. The apostreptic maps show that the structural trends above the sub-Cretaceous on the base Fish Scales and the First White Specks coincide although the former map has the higher relief.

Structural relief is relatively insignificant throughout domain subdivision 2b. Oriented structural trends appear to be confined to the most southerly part of the First White Specks filtered map.

Domain subdivision 2c contains only poorly defined NE-SW trending structures with occasional hints of the orthogonal pattern. The major NW-SE trending linear structure in the central part of the 20 miles NE of Edmonton in domain subdivision 1c, does not appear on the filtered maps of the upper depositional surfaces and its former relief is evidenced by the apostreptic map of the interval immediately over the unconformity. Structures on the two Cretaceous filtered surfaces have about the same spacing and relief (200 feet) except in the NE corner where the First White Specks crops out at the surface. The trend and contour relief is somewhat similar to that of the underlying depositional part of the Devonian surface but the deeper structures are larger, more numerous and have locally higher relief.

The trend, length, width, and average relief of the structures in the filtered maps are significant and part of the rigorous analysis. The following interpretative part of the geometric analysis, that provides meaning to the structural patterns, is not rigorous, but is based on proven trends and can be confidently outlined.

Interpretative Geometric Analysis of the Filtered Maps

An interpretative three-dimensional descriptive analysis requires extrapolation beyond the mathematically rigorous computer output but should remain within the limits imposed by valid geological deduction procedures. If the mathematically valid first part of the geometric analysis is used as a base for a systematically inductive second part then the composite geometric analysis will have a high over all level of significance.

The Interior Plains of Southern Alberta are underlain by a basement of Precambrian rocks. Their radiometric ages of 1600 to 1900 million years places them in an extension of the Churchill province of the Canadian Shield (Burwash, et al, 1964, p. 17). The structural trends in this province which result from the preferred orientation of faults, folds,

gneissosity and magnetic or electromagnetic anomalies (Wilson and Brisbin, 1962) are predominantly either NE-SW or NW-SE (Byers, 1962; Burwash, 1965)

Magnetic maps that permit the basement trends to be followed continuously from the exposed Shield are available for the north-eastern part of the area (Agarwal, 1960, 1962, 1965 a,b,c). This type of map is ideal for establishing the trend of basement structure for it is essentially a measure of the magnetite content of the igneous and metamorphic rocks with only a negligible contribution from overlying sediments.

The basement magnetic trends in the northern part of the area are composed of individual intermediate scale anomalies that parallel the main linear structures in the filtered maps. These magnetic anomalies reflect either basement relief or composition but in either event the features are remarkably coincidental with the structures of the overlying sedimentary surfaces. Burwash (1965) and Kanasewich (1967) describe similar basement patterns in the southern part of the area. The more southerly basement features generally conform to the orthogonal pattern but individual features, like their counterpart structures in the filtered maps, tend to be more isotropic than in the northerly areas. The boundary between subdomains a and b is almost exactly coincident with the division between Precambrian areas of dominantly metamorphic and areas of

dominantly plutonic rocks (Burwash et al, 1964, p. 18). This similarity between the divisions of the sedimentary structural subdomains with those of the basement add weight to the evidence that the basement features are related to those in the overlying sediments.

There is indeed a very high degree of correlation between the trends of the intermediate scale structures in the filtered maps and those in the Precambrian basement. Therefore, the structural trends in the sediments, even though the evidence is circumstantial, may reasonably be assumed to have vertical continuity with those in the older cratonic rocks. There is also evidence that the same structural patterns may appear in the present surface rocks. Erosionally enhanced intermediate scale structures are readily apparent on the outcrop of the First White Specks. Blanchet (1957) found, in aerial photographs, NE-SW and NW-SE trending small scale fracture patterns similar to ones that have been shown to reflect underlying structure in other areas (see e.g. Lattman and Segovia, 1961; Lattman and Matzke, 1961). Barton and Broscoe (1960) pointed out that many linear portions of the drainage channels in southern Alberta reflect underlying structure.

Other surface indications include the NW-SE trending Monarch fault zone (Russell, 1932) that is coincident with a high relief structure on the filtered First White Specks map.

A fault in the Drumheller area strikes NE-SW (Haites, 1960) and possible faults in the Eagle Butte area (Russell and Landes, 1940; Lindoe, 1965) overlie structures apparent on the filtered Cretaceous maps. Surface folds in the southernmost part of the area have their axial planes aligned with the two main orthogonal trends (Russell and Landes, 1940) but do not appear in the filtered maps since they are either small-scale or in the reject portion at the edges of the filtered maps.

Structural patterns that seem to have vertical continuity from the PreCambrian basement to the present surface topography are reflected in all the intermediate scale filtered maps. The individual structures are valid according to the principles of filter theory but there is insufficient factual information for a detailed geometric description. They cannot, on the basis of the filtered maps, be defined as either folds or faults but simply as structural highs and lows. However, the original structural contour maps show that many of the NE-SW trending structures have relatively steep flanks and flattened crests. This tabular appearance and vertical continuity suggest that at least the NE-SW trends are composed of structures that are more likely to be intermediate scale blocks than folds.

Structural relief can only be estimated on the two upper depositional surfaces and on the western part of the

Devonian surface where it is conformably overlain by Mississippian strata. The intermediate scale features on the sub-Cretaceous unconformity owe much of their relief to pre-Cretaceous erosion. Therefore, any measurements of the amplitudes of movements that preceded Cretaceous deposition must be confined to the uneroded parts of the Devonian surface. However, the morphology of the sub-Cretaceous unconformity seems to reflect the underlying structure and so is useful for an interpretation of structural continuity and sequence.

There is conformity between the sub-Cretaceous erosional surface and the underlying structure and individual structures on the Devonian are continuous from the area of Mississippian cover across the unconformity subcrop. The apostreptic map shows that erosion on the unconformity has effectively doubled the original structural relief. This conformity between the erosional and the tectonic structures suggests the increased relief resulted from erosional deepening of preexisting low areas. Since this is more likely to occur in faulted than in folded areas, the erosional patterns tend to support a block movement hypothesis.

Structures on the Devonian surface either exceed in relief or differ in trend from those on the base Fish Scales while conforming in all except erosional relief to those in the overlying Mississippian subcrop. This suggests that some

structural movements occurred during the interval following the beginning of Mississippian deposition and before Cretaceous deposition. The highest amplitude structures on the Devonian surface are confined to domain subdivision la where they have a pronounced NE-SW trend and locally over 500 feet of relief. In this area Cretaceous rocks immediately overlie Jurassic and the morphology of the unconformity is apparently unrelated to the structural patterns on the Devonian surface. The structures on the unconformity are closer spaced, they trend more E-W and seem to coalesce towards the east. This pattern is present only on the unconformity surface and appears to represent a superimposed drainage system. There is also a well developed NE-SW grain to the structural trends in domain subdivision lc with the highest amplitude features concentrated in a belt between Edmonton and Red Deer. This area of higher amplitude features coincides with the location of the early Devonian, Meadow Lake escarpment (Grayson et al., 1964). Similar trends are apparent throughout the remainder of the area but with a reduced amplitude. Differential erosion on the unconformity has uniformly accentuated the structural trends without regard to the original amplitudes.

Domain subdivision lc also exhibits another orthogonally trending series of structures which except for one major linear structure are difficult to distinguish against the background of prominent NE-SW trending structures.

The single major NW-SE trending structural lineation completely disrupts the opposing trend and causes a minimum misalignment of 10 to 15 miles. Erosional relief is uniform on either side of the structure so there is no evidence of vertical offset. The feather edge of the Mississippian swings abruptly and for almost 50 miles follows the western flank of the linear zone whose susceptibility to erosion has caused it to be one of the main drainage channels on the sub-Cretaceous unconformity (Williams, 1963). There is an apparent high feature on the Devonian surface resulting from the change in slope between the depositional and the erosional surface. However, the anomaly has only a very low amplitude and is located to the west of the important NW-SE linear so that there is no effect on the interpretation.

Deeply incised erosion along the structural linear has prevented delineation of the true dimensions or the line of rupture but there can be little doubt that the zone represents a major fault with a minimum lateral displacement of 10 miles. The difficulty of correlating filtered structures prevents any measurement of displacement or sense of displacement. However, the NW-SE trending linear structure and the offset opposing trends are real and the designation of a fault with a strike slip of at least the minimum amount required to

realign the offset structures would seem to be a valid geological description. Since the fault zone has undergone erosion, movement must have taken place prior to the beginning of Cretaceous deposition. Even the erosional channels along the fault were completely infilled during the lower Cretaceous because the trend does not appear even as a compaction feature in the Base Fish Scales map.

The structures on both the erosional and depositional surfaces in domain subdivision 1b are small and generally insignificant. The area must have been rather featureless with only gentle structural movements.

The intermediate scale structural trends in the Cretaceous follow the same general trends that are apparent on the Devonian and Precambrian surfaces. However, movements resulting in a NW-SE trend seem to have been almost entirely restricted to the western part of the area.

The dominant NE-SW sub-Cretaceous trends of domain subdivision 1a become increasingly subordinate throughout the Cretaceous until only NW-SE trending structures with high relief are apparent in the maps on the First White Specks. The Base Fish Scales is intermediate in the change of emphasis with a NE-SW trending structure discernible in a dominantly NW-SE structural grain. Surface structures such as the Monarch

fault zone (Russell, 1932) are parallel to those in the First White Specks.

Domain subdivision 2b continued relatively stable with the only significant intermediate scale structural activity confined to the most southerly part. The structures are most prominent on the First White Specks and in such surface areas as Deadhorse Coulee or Taber (Russell and Lanes, 1940,p. 107, 118).

The Cretaceous maps show that there have been structural movements that resulted in up to 200 feet of relief after Lower Cretaceous deposition. Diminished relief on the First White Specks suggests the activity was not confined to one period but was continued over much of the Upper Cretaceous. The amplitude of the movements was relatively minor for the main trend directions require the 50 foot contours of the computer maps (Figures 35 and 36) for confirmation. The 50 foot contours cannot be considered rigorous but they can be used to interpret the trends of continuous linear structures with a high degree of confidence.

The interpreted Upper Cretaceous structural trends are predominantly NE-SW but there are, particularly in the western part of the area, subsidiary NW-SE trending structures. There appears to be some reflection of the trends on the surface.

This surface structural amplitude is difficult to estimate but is certainly much less than the amount evident in the First White Specks map.

The intermediate scale structures are primarily interpreted as tabular blocks with essentially vertical boundaries that appear to extend into the Precambrian basement. The majority of the structures appear to be defined by differential vertical relief but there is at least one instance where there is a pronounced lateral offset.

Kinematic and Dynamic Analysis

The geometric analysis has established that there is a strong likelihood of vertical continuity between the intermediate scale structures in the sediments and the apparently similar structures in the underlying Precambrian basement. The movements in the vertical plane have been relatively gentle with most displacements totalling less than 200 feet and only locally reaching as much as 500 feet. The largest movement was the 10 to 15 mile minimum strike slip along the NW-SE trending wrench fault in the area 20 miles northeast of Edmonton.

The small vertical movements and the limited resolving power of the information in the well control permit only a

very rough approximation of the tectonic events that caused the structures. Since the structures have vertical coincidence, the planes of movement must have been at a very high angle and would therefore have originated in conjunction with the underlying basement structures. The NW-SE trending wrench fault in the area north of Edmonton has a minimum of 10 miles strike slip and likely is also of basement origin. The present data rigorously shows the structural offset but is insufficient information for calculation of the real displacement or even the sense of displacement. However, a possible offset in the continuity of the Leduc-Rimbey and the Morinville reef trends (Belyea, 1960) suggest the movement may have been sinistral.

Tectonic movements that caused the NE-SW trending structures exhibited on the Devonian surface were of relatively minor amplitude. They were essentially vertical basement adjustments that produced tabular structures with a maximum of 500 feet of local structural relief. The early essentially linear structures in the northern part of the area were then offset by wrench faulting. Movement on the fault subsided before the beginning of Cretaceous deposition.

Following the period of faulting, movements on both the NE-SW and the NW-SE trends were entirely confined to small amplitude vertical adjustments. Also, concentrated along the western margins of the uppermost surfaces, there are also minor

folds that appear to be a surfical extension of the Rocky Mountain disturbed belt. The latter structures appear as folds in the original structural countour maps and are distinct from the basement controlled tabular features.

The dynamic relationships are entirely speculative. However, the structural patterns are similar to those in the basement that were determined during the Precambrian orogenic periods long before the present sediments were deposited. The structural movements that produced the present large scale basement configuration (Burwash, 1964, p. 18) undoubtedly set up local stress variations that would account for the vertical adjustments along the old intermediate scale zones of weakness. In addition, the main wrench fault would suggest a system of horizontal shear stresses similar in pattern, but not necessarily in direction, to those proposed by Byers (1962) for the western part of the Canadian Shield. These shear forces must have been active as recently as the regressive period when the sub-Cretaceous unconformity was formed.

Large Scale Structures

The prominent large scale structural elements are illustrated on the structural contour maps (Figures 3 to 7). However, additional ones may be inferred from the relief of

their contained intermediate scale erosional structures as shown on the filtered map of the unconformity (Figure 52). This inference is based on the assumption that areas of deep erosional incisement have originally had a higher relative elevation than adjacent areas of less pronounced erosional activity The measure is not considered precise but only serves to distinguish upland areas from the lower, less erosionally active plains.

In southern Alberta the erosional relief on the sub-Cretaveous unconformity distinguishes three areas of different surface elevation. Domain subdivision la (Figure 58) has the most deeply incised erosional features with over 300 feet of erosional relief. The erosional pattern suggests a drainage system with streams flowing into the low relief area to the east. The erosional relief and the morphology suggests there was an area of relatively high elevation during the time of sub-Cretaceous erosion located in the southwest corner of the area and roughly corresponding to the position of the West Alberta Arch.

The erosional relief in domain subdivision lb is generally under 200 feet and relatively uniform over the entire area. The low relief and the lack of a pronounced drainage pattern suggests a stable lowland area contrasted to the higher domains. To the north and across a dividing line that follows the eastern swing of the Mississippian subcrop

edge, domain subdivision c has erosional relief averaging 400 feet. The deeply incised erosional features and the drainage morphology (Williams, 1963), particularly the tributaries that trend NE-SW, suggests this area could have been at a higher elevation than its neighbor to the south. However, the main drainage follows the course of the wrench fault and is to the NW suggesting the less likely but alternative interpretation that domain subdivision c is the eroded portion of a formerly extensive plain with domain subdivision b the uneroded remainder. In this case there would be a decrease in elevation from a to c and the boundary between b and c may be either erosional or tectonic.

During the sub-Cretaceous period of erosion the large scale structures of southern Alberta appeared to consist of three blocks with different relative elevations. The boundaries between the blocks follow older structural elements and outline subdivisions of differing intermediate scale structural activity.

Summary

The spatially filtered structural contour maps permit elucidation of the history of the intermediate scale structures of the Interior Plains of Southern Alberta. The events and their sequence are valid for the stratigraphic

interval spanned by the maps, but become hypothetical when the interpretation is extended much beyond their limits.

Two directionally stable, orthogonal, intermediate scale structural trends dominate all maps. Structures with these trends and associated areas of uniform structural amplitude probably reflect the architecture of the underlying Precambrian basement.

Structures developed after the beginning of Mississippian deposition and prior to the beginning of Cretaceous deposition (Figure 59) can be identified in the filtered structural contour maps. The structures are generally tabular and are aligned NE-SW with zones of highest amplitude confined to the southwest corner of Alberta and to the central area between Edmonton and Red Deer. The first zone is located on the West Alberta Arch (Ridge), a large scale structural high that was prominent during the lower Paleozoic (van Hees and North, 1964; Grayston, et al.,1964). The second area overlies the Meadow Lake escarpment where there was previously known tectonic activity as recently as the middle Devonian (Grayston, et al., 1964; Jones, 1965).

Although there were previous vertical movements on the NW-SE boundaries of the tabular blocks, the first well defined structure on the second main trend was a wrench fault that laterally offset the NE-SW trending structures by at least

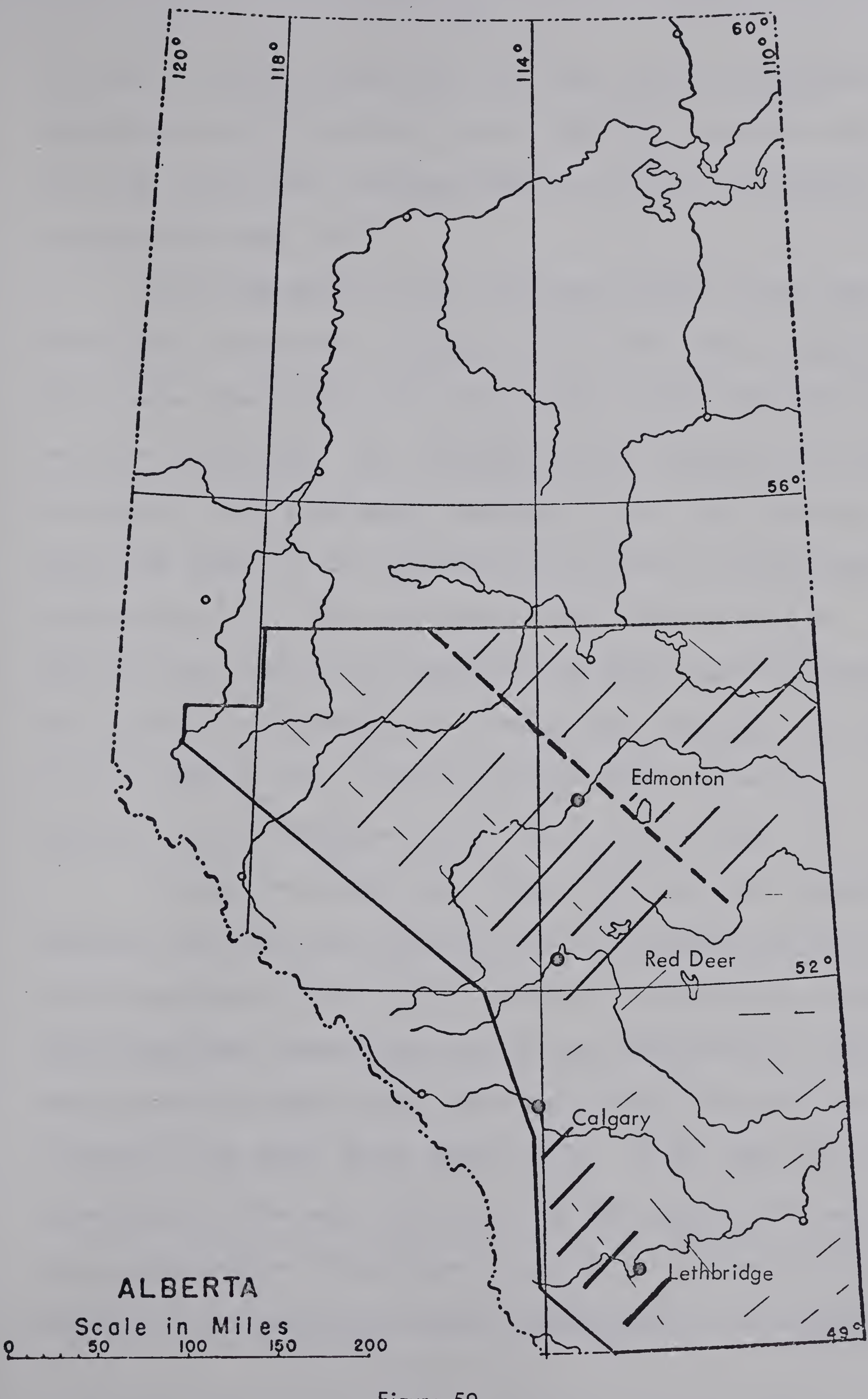

Figure 59

Main pre-Cretaceous structural trends in southern Alberta.

10 miles. Movement along the fault was prior to Cretaceous deposition and differential erosion deformed the shear zone into one of the main drainage channels on the unconformity surface (Williams, 1963).

The intermediate scale erosional relief on the sub-Cretaceous unconformity suggests that at the time of erosion there were three large scale structural blocks with different relative elevations. The erosional relief suggests the area of highest elevations again conformed to the West Alberta Arch, the lowest to the generally structurally stable domain subdivision b. To the north and on the other side of a dividing line immediately south of the Meadow Lake escarpment and roughly corresponding to a Precambrian boundary, (Burwash et al., 1964, p. 18) a third block was at an elevation estimated as intermediate to the two southern ones.

During Cretaceous time (Figure 60) there was renewed tectonic activity producing relatively high amplitude structures in the southwest "Arch" area. However, the previously strong NE-SW structual trends gradually became subordinate to the NW-SE trends so that by late Cretaceous only the latter are evident in the First White Specks maps. At the same time and immediately to the east the uplift of the large scale Sweet Grass Arch (Figure 3) produced a scatter of intermediate scale structures that are most readily recognized on the First White

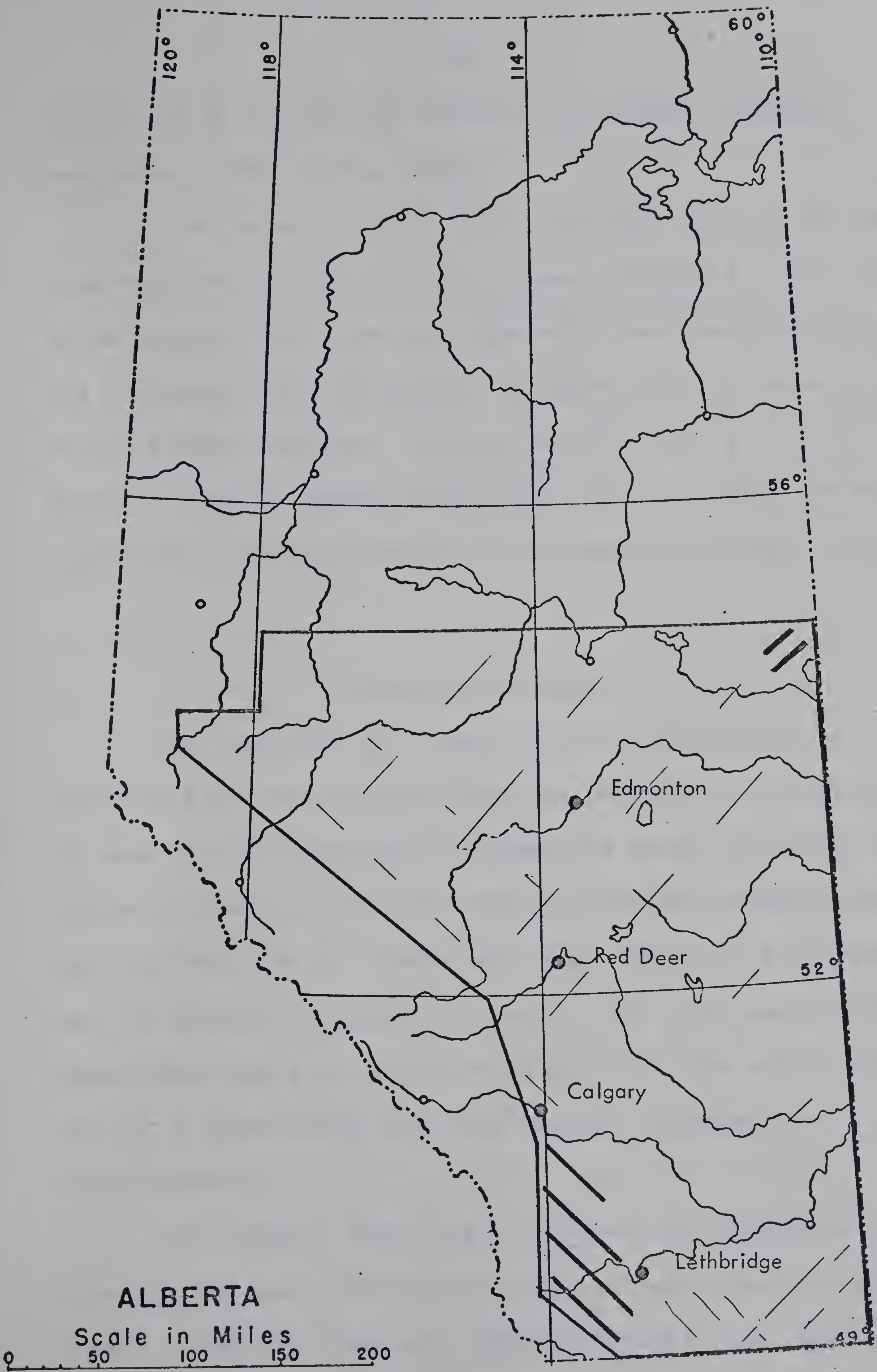

Figure 60

Main Cretaceous structural trends in southern Alberta.

Specks and on the present surface outcroppings (Russell and Landes, 1940; Alpha, 1955).

Cretaceous activity in the northern part of the map area resulted in additional structural movements on the old NE-SW trends. This movement apparently continued throughout the Cretaceous and the pattern is discernible in the morphology of the present surface. Activity on the NW-SE structural trend seemed to nearly subside during the Cretaceous with the only significant activity confined to the western part of the area.

Future Developments

The application of spatial filtering methods to a suite of structural contour maps has permitted the definition of some of the significant intermediate scale structures of southern Alberta. The coincidence of the Bon Accord, Fairydell and Westlock gas fields with the underlying fault zone and the apparent alignment of many of the other gas and oil fields with the structural trends point out the strong likelihood of a depositional and thus economic dependence on structural controls.

The present study has only proven the existence of intermediate scale structures and illustrated some of their trends. However, there are known structures (e.g. the Leduc-Rimbey reef trend) that do not appear to fit the patterns and

there are undoubtedly many other and as yet undiscovered structural controls that remain to be defined in future studies.

Fortunately, exploratory wells are continually being drilled and form additions to the available information so that eventually, possibly in conjunction with seismic and other geophysical data, filtered maps may aid in an interpretation that could lead to a more complete understanding of the tectonic history of Western Canada. An integrated tectonic and stratigraphic picture on the scale of the structures that confine petroleum could be a very important economic tool.

REFERENCES

Agarwal, R.A., (1960): Interpretation of aeromagnetic data in west central Saskatchewan and east central Alberta; Sask. Dept. of Mineral Resources, rep. no. 63, 17 pages.

_______________(1962): Regional correlation of geological and geophysical data in the Lake Athabasca area, northern Saskatchewan; Sask. Dept. Mineral Res., report 75, 4 pages.

_______________(1965a): Regional correlation of geological and geophysical data in the Wollaston Lake area, northern Saskatchewan; Sask. Dept. Mineral Resources, report 82, 4 pages.

_______________(1965b): Regional correlation of geological and geophysical data in the Cree Lake area, northern Saskatchewan; Sask. Dept. Mineral Res., report 94, 4 pages.

Agocs, W.B., (1951): Least squares residual anomaly determination; Geophysics, Vol. 16, p. 686-696.

Alberta Society of Petroleum Geologists, (1960): Lexicon of geologic names in the western Canada sedimentary basin and Arctic Archipelago: Alta. Soc. Petroleum Geol., 380 pages.

Alpha, A.G., (1955): Tectonic history of north central Montana; Billings Geol. Soc. Guidebook, 6th Annual Field Conf., p. 129-142.

Andrichuk, J.M., (1961): Stratigraphic evidence of tectonic and current control of Upper Devonian reef sedimentation in the Duhamel area, Alberta, Canada; Bull. Amer. Assoc. Petroleum Geol., Vol. 45, p. 612-632.

Anstey, N.A., (1965): Wiggles; Journ. Can. Soc. Expl. Geophysicists, Vol. 1, p. 13-43.

Barton, R.H., and Broscoe, A.J., (1960): The geomorphic expression of selected concealed structures in western Canada; Preprints of Papers, Amer. Assoc. Petroleum Geol. and Alta. Soc. Petroleum Geol., joint meeting, Banff, p. 74-81.

Belyea, H.R., (1960): Distribution of some reefs and banks of the Upper Devonian Woodbend and Fairholme Groups in Alberta and eastern British Columbia; Geol. Survey of Canada, paper 59-65, 7 pages.

Belyea, H.R., Moyer, G.L., Greg F.F., and Grayson, L.D., (1964): Upper Devonian; In Geological History of Western Canada, (ed. McCrossan, R.G., and Glaister, R.P.): Alta. Soc. Petroleum Geol., p. 14-19.

Bhattacharyya, B.K., (1965): Two-dimensional harmonic analysis as a tool for magnetic interpretation; Geophysics. Vol. 30, p. 829-857.

Bhattacharyya, B.K., and Raychaudhuri, B., (1967): Aeromagnetic and geological interpretation of a section of the Appalachian belt in Canada; Can. Journal Earth Sciences, Vol. 4, p. 1015-1037.

Blackman., R.B., and Tukey, J.W., (1958): The Measurement of power spectra; Dover Publications, 190 pages.

Blanchet, P.H., (1957): Development of fracture analysis as exploration method; Bull. Amer. Assoc. Petroleum Geol., Vol. 41, p. 1748-1759.

Borden, R.L., (1956): Historical Geology and tectonics of the southern part of the prairie provinces, Canada: Journ. Alta. Soc. Pet. Geologists, Vol. 4, No. 6, p. 134-140.

Burwash, R.A., Baadsgaard, H., Peterman, Z.E., and Hunt, G.H., (1964): Precambrian; In Geological History of Western Canada (ed. McCrossan, R.G., and Glaister, R.P.); Alta. Soc. Petroleum Geol., p. 14-19.

Burwash, R.A., (1965): Basement architecture of western Canada; Alta. Soc. Petroleum Geol., 15th Annual Fld. Conf. Guidebook, pt. 1, p. 280-288.

Byers, A.R., (1962): Major faults in western part of Canadian Shield with special reference to Saskatchewan; In the tectonics of the Canadian Shield (ed. Stevenson, J.S., Royal Soc. Can., Spec. Pub. no. 4, University of Toronto Press, p. 40-59.

Danes, Z.F. and Oncley, L.A., (1962): An analysis of some second deritive methods; Geophysics, Vol.27, p. 611-615.

Dawson, G.M., and McConnell, R.G., (1885): Report on the region in the vicinity of the Bow and Belly Rivers, North-west Territory; Canada, Geol. Surv. Report Prog. 1882-1884. pt. c, 168 pages.

Dean, W.C., (1958): Frequency analysis for gravity and magnetic interpretation; Geophysics, Vol. 23, p. 97-127.

DeMille, G., Lavoie, D.H., Williams, G.K., and Macauley, G., (1958): Symposium on the Peace River arch; Journ. Alta. Soc. Petroleum Geol., Vol. 6, p. 60-86.

Dowling, D.B., (1917): The southern plains of Alberta; Geol. Sur. Can., Memoir 93, 200 pages.

Dowling, D.B., Slipper, S.E., and McLearn, F.H., (1919): Investigations in the Gas and Oil Fields of Alberta, Saskatchewan, and Manitoba; Geol. Survey of Canada, Memoir 116, 89 pages.

Gentleman, W.M., and Sande, G., (1966): Fast Fourier transforms - for fun and profit; AFIPS, Proceedings - Fall Joint Computer Conference, Vol. 29, p. 563-578.

Good, D.I., (1964): Fortran 11 trend surface program for the IBM 1620; Spec. Dist. Pub. 14, State Geol. Sur., University of Kansas, 54 pages.

Goldman, S., (1953): Information theory; Prentice-Hall Inc., New York, 385 pages.

Grant, F., (1957): A problem in the analysis of geophysical data; Geophysics, Vol. 22, p. 309-344.

Grant, F.S., and West, G.F., (1965): Interpretation theory in applied Geophysics; McGraw-Hill Book Comp. Inc., N.Y., 583 pages.

Grayston, L.D., Sherwin, D.F., and Allan, J.F., (1964): Middle Devonian; (ed. McCrossan, R.G., and Glaister, R.P.); In Geological history of western Canada; Alta. Soc. Petroleum Geol., p. 39-59.

Griffin, W.R., (1949): Residual gravity in theory and practice; Geophysics, Vol. 14, p. 39-56.

Haites, T.B., (1960): Transcurrent faults in western Canada; Journal Alta. Soc. Petroleum Geol., Vol. 8, p. 33-78.

Harbaugh, J.W., (1963): Balgol program for trend-surface mapping using an IBM 7090 computer; Spec. Dist. Publ. 3, State Geol. Sur., University of Kansas, 17 pages.

Harbaugh, J.W., and Preston, F.W., (1965): Fourier series analysis in Geology; In symposium on computers and computer applications in mining and exploration; (ed. Dotson, J.C., and Peters, W.C.), college of mines, University of Arizona, Vol. 1, p. R1-R46.

Henderson, R.G., and Zeitz, I., (1949): The computation of second vertical deritives of geomagnetic fields; Geophysics, Vol. 14, p. 508-516.

Hitchon, B., (1964): The effect of differences in interpretation on the lithological evaluation of electric logs; Bull. Can. Petroleum Geol., Vol. 12, p. 754-759.

Holloway, J.L., (1958): Smoothing and filtering of time series and space fields; Advances in Geophysics, Vol. 4; Academic Press Inc., p. 351-389.

Hume, G.S., (1933): Oil and gas in western Canada; Geol. Surv. Can., Econ. Geol. Ser. 5, 359 pages.

James, W.R., (1966): Fortran 1V program using double Fourier series for surface fitting of irregularly spaced data; Computer contribution 5, State Geol. Surv. University of Kansas, 17 pages.

Jones, L., (1965): The middle Devonian, Winnipegosis Formation of Saskatchewan; Sask. Depart. Mineral Res., report 98, 101 pages.

Kanasewich, E.R., (1967): A buried precambrian rift in western Canada; Abstract, Upper Mantle Committee, Symposium on Rifts, Zurich, Germany.

Krumbein, W.C., (1956): Regional and local components in facies maps; Bull. Amer. Assoc. Petroleum Geol., Vol. 40, p. 2163-2194.

________________(1959): Trend surface analysis of contour-type maps with irregular control-point spacing; Jour. Geophysical Research, Vol. 64, p. 823-834.

Krumbein, W.C., and Graybill, F.A., (1965): An introduction to

statistical models in Geology; McGraw-Hill Book Co., New York, 475 pages.

Lattman, L.H., and Matzke, R.H., (1961): Geological significance of fracture traces; Photogrammetric Engineering, Vol. 27, p. 435-438.

Lattman, L.H., and Segovia, A.V., (1961): Analysis of fracture trace pattern of Adak and Kagaloska islands, Alaska; Bull. Amer. Assoc. Pet. Geol., Vol. 45, p. 249-263.

Lee, Y.W., (1960): Statistical theory of communication; John Wiley and Sons, New York, 509 pages.

Levorsen, A.I., (1927): Convergence studies in the mid-continent region; Amer. Assoc. Pet. Geol., Vol. 11, p. 657-682.

Lindoe, L.O., (1965): Ceramic clays of the Cypress Hills; Alta. Soc. Pet. Geol., 15th Annual Fld. Conf., Guide-book, pt. 1., p. 210-225.

Marshall, J.L., (1965): Introduction to signal theory; Inter. Textbook Co., Scranton, Pa., 254 pages.

McCrossan, R.G., and Glaister, R.P., (editors), (1964): Geological history of western Canada; Alta. Soc., Petroleum Geol., 232 pages.

Merriam, D.F., and Cocke, N.C., (editors), (1967a): Computer applications in the earth sciences: colloquium on trend analysis; Computer Cont. 10, State Geol. Surv., University of Kansas, Lawrence, 62 pages.

Miller, R.L., (1956): Trend surfaces: their application to analysis and description of environments of sedimentation; Jour. Geology, Vol. 64, p. 425-446.

Miller, R.L. and Kahn, J.S., (1962): Statistical analysis in the geological sciences; John Wiley and Sons, Inc., New York, 483 pages.

Morley, L.W., and Bhattacharyya, B.K., (1966): Quantitive treatment of aeromagnetic data in mineral areas; Can. Inst. Min. Met. Bull., Vol. 59, p. 733-742.

Nettleton, L.L., (1954): Regionals, residuals and structures; Geophysics, Vol. 19, p. 1-22.

Oil and Gas Conservation Board, (1966): Table of Formations; O.G.C.B., Calgary.

Oldham, C.H.G., and Sutherland, D.B., (1955): Orthogonal polynomials: their use in estimating the regional effect; Geophysics, Vol. 20, p. 295-306.

O'Leary, M., Lippert, R.H., and Spitz, O., (1966): Fortran lV and map program for computation and plotting of trend surfaces for degrees 1 through 6; Computer contribution 3, State Geol. Survey, University of Kansas, Lawrence, 47 pages.

Peters, L.J., (1949): The direct approach to magnetic interpretation and its practical application; Geophysics, Vol. 14, p. 290-320.

Peterson, R.A., and Dobrin, M.B., (editors), (1966): A pictorial digital atlas; United Geophysical Corp., Pasedena, Calif., p. 53.

Rich, J.L., (1935a): Graphical methods for eliminating regional dip; Bull. Amer. Assoc. Petroleum Geol., Vol. 19, p. 1538-1540.

_____________(1935b): Fault block nature of Kansas structures suggested by elimination of regional dip; Bull. Amer. Assoc. Petroleum Geol., Vol. 19, p. 1540-1543.

Robinson, E.A., and Treitel, S., (1964): Principles of digital filtering; Geophysics, Vol. 29, p. 395-404.

Russell, L.S., (1932): Stratigraphy and structure of the Eastern portion of the Blood Indian reserve, Alberta; Geol. Surv. of Canada, Summary report (1931), part B., p. 26-38.

Russell, L.S., and Landes, R.W., (1940): Geology of the southern Alberta plains; Geol. Surv. Can., Memoir 221, 223 pages.

Sikabonyi, L.A., (1957): Tectonic trends in the prairie region of western Canada; Jour. Alta. Soc. Petroleum Geol., Vol. 5, p. 23-28

Sikabonyi, L.A., and Rodgers, W.J., (1959): Paleozoic tectonics and sedimentation in the northern half of the west Canadian basin: Jour. Alta. Soc. Petroleum Geol., Vol. 7, p. 193-216.

Simpson, S.M., (1954): Least squares polynomial fitting to gravitational data and density plotting by digital computers; Geophysics, Vol. 19, p. 255-269.

Swartz, C.A., (1954): Some geometrical properties of residual maps; Geophysics, Vol. 19, p. 46-70.

Turner, F.J., and Weiss, L.E., (1963): Structural analysis of metamorphic tectonites; McGraw-Hill Book Company, Inc., New York, 545 pages.

van Hees, H., and North, F.K., (1964): Cambrian: (ed. McCrossan, R.G., and Glaister, R.P., In Geological History of western Canada; Alta. Soc. Petroleum Geol., p. 20-33.

Webb, J.B., (1954): Geological history of plains of western Canada; In western Canada sedimentary basin (ed. Clark, L.M.). Amer. Assoc. Petroleum Geol., p. 3-28.

Williams, G.D., (1963): The Mannville group (Lower Cretaceous) of central Alberta; Bull. Can. Petroleum Geol., Vol. 11, p. 350-368.

Williams, M.Y., and Dyer, W.S., (1930): Geology of southern Alberta and southwestern Saskatchewan; Geol. Surv. of Canada, Memoir 163, 160 pages.

Wilson, H.D.B., and Brisbin, W.C., (1962): Tectonics of the Canadian Shield in northern Manitoba; In tectonics of the Canadian Shield (ed. Stevenson, J.S.): Royal Soc. of Can., Spec. Publ. 4, University of Toronto Press, p. 60-75.

Zurflueh, E.G., (1967): Application of two-dimensional linear wavelength filtering; Geophysics, Vol. 32, p. 1015-1035.

APPENDIX

Program 1

Main program and subroutines for computing a one-dimensional Fourier transform from a distance domain digitized cross section.

Input to the program is:

Format (5X,I5)	-	input device
Format (5X,I5)	-	number of digital values
	-	must be factorable into numbers not greater than 13.
Format (5X,F8.3)	-	digital interval in miles
Format (4X,10F5.0)	-	input digital values as a continuous vector beginning with the center of the section

The output is in the same order as the input vector and includes the real amplitude, imaginary amplitude, power absolute amplitude and phase.

```
C       THIS PROGRAM CALCULATES A ONE DIMENSIONAL FOURIER TRANSFORM USING
C       AN ALGORITHM OF GOOD (1958) AS MODIFIED BY COOLEY-TUKEY (1966)
C       AND GENTLEMAN-SANDE (1966)
C
C       X(J)+IY(J) IS THE COMPLEX VECTOR USED IN SUBROUTINE FOUR 1D
C       X(J) IS REAL AND Y(J)=0.0
C       NOPTS    ***** THE NUMBER OF DATA POINTS
C       DELT    ***    THE DIGITIZING INTERVAL IN MILES
C       INPUT    ***    UNIT FROM WHICH DATA IS TO BE READ
        COMMON/DAT/X(3000),Y(3000)
        COMMON/CONST/NOPTS
        REAL AMPL,PHASE
     10 FORMAT (5X,I5)
     20 FORMAT (5X,I5)
     30 FORMAT (5X,F8.3)
     35 FORMAT(4X,10F5.0)
     40 FORMAT (1X,10HINPUT DATA)
     50 FORMAT (1HT,14X,53H***********************************************
       1******)
     60 FORMAT (1X,5HDELT=,F8.3,1X,18HNYQUIST FREQUENCY=,F8.3)
     70 FORMAT (1X,8HNOPTS = ,I5)
     80 FORMAT (1X,12HFREQUENCY=J*,F10.6,1X,17HCYCLES PER MILE  )
    100 FORMAT (1HK,40X,33HONE DIMENTIONAL FOURIER TRANSFORM)
    110 FORMAT (1HT,39X,33H*********************************)
    120 FORMAT(5X,2H J,7X,4HR(J),23X,5HIM(J),15X,5HPOWER,16X,9HAMPLITUDE,
       113X,5HPHASE)
    130 FORMAT(1X,I6,5X,4(F11.4,10X),F11.4)
        READ (5,10) INPUT
        WRITE(6,99)
     99 FORMAT('1')
        READ (5,20) NOPTS
        READ (5,30) DELT
        READ (INPUT,35)  (X(J),J=1,NOPTS)
        WRITE (6,40)
        WRITE (6,35)  (X(J),J=1,NOPTS)
        WRITE (6,50)
        FN = 1./(2.*DELT)
        WRITE (6,60) DELT,FN
        WRITE (6,70) NOPTS
        FP=(FN*2.0)/(FLOAT(NOPTS))
        WRITE (6,80) FP
        SUM=0
        DO 88 J=1,NOPTS
        SUM=SUM+X(J)
     88 CONTINUE
        AVER=SUM/FLOAT(NOPTS)
        DO 89 J=1,NOPTS
        X(J)=X(J)-AVER
     89 CONTINUE
        DO 90 J=1,NOPTS
        Y(J) = 0.0
     90 CONTINUE
        CALL FOUR 1D
        CALL SORT 1D
        WRITE (6,100)
        WRITE (6,110)
        WRITE (6,120)
    190 CONTINUE
        DO 140 J=1,NOPTS
        IF((X(J).GE.1.0E7).OR.(Y(J).GE.1.0E7))GOTO 170
```

```
      POWFR=X(J)**2+Y(J)**2
      AMPL = SQRT(X(J)**2+Y(J)**2)
      IF (X(J).EQ.0.0)GO TO 210
      PHASE = ATAN2(Y(J),X(J))
      PHASE=(3.14159*PHASE)/180.0
      GO TO 220
  210 PHASE=0
  220 WRITE(6,130)J,X(J),Y(J),POWFR,AMPL,PHASE
  140 CONTINUE
      GOTO 200
  170 CONTINUE
      DO 180 J=1,NOPTS
      X(J)=X(J)*.001
      Y(J)=Y(J)*.001
  180 CONTINUE
      GOTO 190
  200 CONTINUE
      STOP
      FND
```

```
      SUBROUTINE  FOUR 1D
C     ONE DIMENSIONAL FOURIER TRANSFORM
C
      COMMON/DAT/X(3000),Y(3000)
      COMMON/CONST/NOPTS
C
      INTEGER J,K,M,MR,J1,J2,J3,J4,J5,JT
      REAL I1,I2,I3,I4,I5
      INTEGER P,PMAX,U,V
C
C     NEEDS SORT 1D  TO RECOVER UNSCRAMBLED FOURIER COEFFICIENTS
C
C     THIS SUBROUTINE REPLACES X + I Y BY ITS FOURIER TRANSFORN WHERE
C     X(F)+IY(F)  = SUM T=0,(NOPTS-1) OF (X(T)+IY(T))*EXP(-F*T/NOPTS).
C
C     REAL I (PMAX), R (PMAX), C (PMAX,PMAX), S (PMAX,PMAX),
C    .A ((PMAX-1)**2+1), B ((PMAX-1)**2+1)
C
      REAL I (13), R (13), C (13,13), S (13,13), A (145), B (145)
C
      PMAX=13
C
      TWOPI=6.283185307
      M=NOPTS
  100 CONTINUE
      IF (M.NE.(M/4)*4) GO TO 400
C
C     FACTORS OF FOUR
C
      MR=M
      M=M/4
```

```
      DO 300 J=1,M
      ARG=TWOPI*FLOAT(J-1)/FLOAT(MR)
      C1=COS(ARG)
      S1=SIN(ARG)
      C2=COS(2.0*ARG)
      S2=SIN(2.0*ARG)
      C3=COS(3.0*ARG)
      S3=SIN(3.0*ARG)
      DO 200 K=MR,NOPTS,MR
      J1=J+K-MR
      J2=J1+M
      J3=J2+M
      J4=J3+M
      R1=X(J1)+X(J3)
      R2=X(J1)-X(J3)
      I1=Y(J1)+Y(J3)
      I2=Y(J1)-Y(J3)
      R3=X(J2)+X(J4)
      R4=X(J2)-X(J4)
      I3=Y(J2)+Y(J4)
      I4=Y(J2)-Y(J4)
      X(J1)=R1+R3
      Y(J1)=I1+I3
      X(J2)=(R2+I4)*C1+(I2-R4)*S1
      Y(J2)=(I2-R4)*C1-(R2+I4)*S1
      X(J3)=(R1-R3)*C2+(I1-I3)*S2
      Y(J3)=(I1-I3)*C2-(R1-R3)*S2
      X(J4)=(R2-I4)*C3+(I2+R4)*S3
      Y(J4)=(I2+R4)*C3-(R2-I4)*S3
  200 CONTINUE
  300 CONTINUE
      GO TO 100
  400 CONTINUE
      IF (M.NE.(M/2)*2) GO TO 700
C
C     FACTORS OF TWO
C
      MR=M
      M=M/2
      DO 600 J=1,M
      ARG=TWOPI*FLOAT(J-1)/FLOAT(MR)
      C1=COS(ARG)
      S1=SIN(ARG)
      DO 500 K=MR,NOPTS,MR
      J1=J+K-MR
      J2=J1+M
      R1=X(J1)+X(J2)
      R2=X(J1)-X(J2)
      I1=Y(J1)+Y(J2)
      I2=Y(J1)-Y(J2)
      X(J1)=R1
      Y(J1)=I1
      X(J2)=R2*C1+I2*S1
      Y(J2)=I2*C1-R2*S1
  500 CONTINUE
  600 CONTINUE
      GO TO 400
  700 CONTINUE
      IF (M.NE.(M/3)*3) GO TO 1000
C
```

```
C       FACTORS OF THREE
C
        MR=M
        M=M/3
        A1=COS(TWOPI/3.0)
        B1=SIN(TWOPI/3.0)
        A2=COS(2.0*TWOPI/3.0)
        B2=SIN(2.0*TWOPI/3.0)
        DO 900 J=1,M
        ARG=TWOPI*FLOAT(J-1)/FLOAT(MR)
C
C       ABSORB TWIDDLE FACTOR INTO ANALYSIS COEFFICIENTS
C
        C21=COS(ARG)
        S21=SIN(ARG)
        C22=C21*A1-S21*B1
        S22=C21*B1+S21*A1
        C23=C21*A2-S21*B2
        S23=C21*B2+S21*A2
        C31=COS(2.0*ARG)
        S31=SIN(2.0*ARG)
        C32=C31*A2-S31*B2
        S32=C31*B2+S31*A2
        C33=C31*A1-S31*B1
        S33=C31*B1+S31*A1
        DO 800 K=MR,NOPTS,MR
        J1=J+K-MR
        J2=J1+M
        J3=J2+M
        R1=X(J1)
        I1=Y(J1)
        R2=X(J2)
        I2=Y(J2)
        R3=X(J3)
        I3=Y(J3)
        X(J1)=R1+R2+R3
        Y(J1)=I1+I2+I3
        X(J2)=R1*C21+I1*S21+R2*C22+I2*S22+R3*C23+I3*S23
        Y(J2)=I1*C21-R1*S21+I2*C22-R2*S22+I3*C23-R3*S23
        X(J3)=R1*C31+I1*S31+R2*C32+I2*S32+R3*C33+I3*S33
        Y(J3)=I1*C31-R1*S31+I2*C32-R2*S32+I3*C33-R3*S33
  800   CONTINUE
  900   CONTINUE
        GO TO 700
 1000   CONTINUE
        IF (M.NE.(M/5)*5) GO TO 1300
C
C        FACTORS OF FIVE
C
        MR=M
        M=M/5
        A1=COS(TWOPI/5.0)
        B1=SIN(TWOPI/5.0)
        A2=COS(2.0*TWOPI/5.0)
        B2=SIN(2.0*TWOPI/5.0)
        A3=COS(3.0*TWOPI/5.0)
        B3=SIN(3.0*TWOPI/5.0)
        A4=COS(4.0*TWOPI/5.0)
        B4=SIN(4.0*TWOPI/5.0)
        DO 1200 J=1,M
```

```
      ARG=TWOPI*FLOAT(J-1)/FLOAT(MP)
C
C     ABSORB TWIDDLE FACTOR INTO ANALYSIS COEFFICIENTS
C
      C21=COS(ARG)
      S21=SIN(ARG)
      C22=C21*A1-S21*B1
      S22=C21*B1+S21*A1
      C23=C21*A2-S21*B2
      S23=C21*B2+S21*A2
      C24=C21*A3-S21*B3
      S24=C21*B3+S21*A3
      C25=C21*A4-S21*B4
      S25=C21*B4+S21*A4
      C31=COS(2.0*ARG)
      S31=SIN(2.0*ARG)
      C32=C31*A2-S31*B2
      S32=C31*B2+S31*A2
      C33=C31*A4-S31*B4
      S33=C31*B4+S31*A4
      C34=C31*A1-S31*B1
      S34=C31*B1+S31*A1
      C35=C31*A3-S31*B3
      S35=C31*B3+S31*A3
      C41=COS(3.0*ARG)
      S41=SIN(3.0*ARG)
      C42=C41*A3-S41*B3
      S42=C41*B3+S41*A3
      C43=C41*A1-S41*B1
      S43=C41*B1+S41*A1
      C44=C41*A4-S41*B4
      S44=C41*B4+S41*A4
      C45=C41*A2-S41*B2
      S45=C41*B2+S41*A2
      C51=COS(4.0*ARG)
      S51=SIN(4.0*ARG)
      C52=C51*A4-S51*B4
      S52=C51*B4+S51*A4
      C53=C51*A3-S51*B3
      S53=C51*B3+S51*A3
      C54=C51*A2-S51*B2
      S54=C51*B2+S51*A2
      C55=C51*A1-S51*B1
      S55=C51*B1+S51*A1
      DO 1100 K=MR,NOPTS,MR
      J1=J+K-MR
      J2=J1+M
      J3=J2+M
      J4=J3+M
      J5=J4+M
      R1=X(J1)
      I1=Y(J1)
      R2=X(J2)
      I2=Y(J2)
      R3=X(J3)
      I3=Y(J3)
      R4=X(J4)
      I4=Y(J4)
      R5=X(J5)
      I5=Y(J5)
```

```
      X(J1)=R1+R2+R3+R4+R5
      Y(J1)=I1+I2+I3+I4+I5
      X(J2)=R1*C21+I1*S21+R2*C22+I2*S22+R3*C23+I3*S23+R4*C24+I4*S24+
     .R5*C25+I5*S25
      Y(J2)=I1*C21-R1*S21+I2*C22-R2*S22+I3*C23-R3*S23+I4*C24-R4*S24+
     .I5*C25-R5*S25
      X(J3)=R1*C31+I1*S31+R2*C32+I2*S32+R3*C33+I3*S33+R4*C34+I4*S34+
     .R5*C35+I5*S35
      Y(J3)=I1*C31-R1*S31+I2*C32-R2*S32+I3*C33-R3*S33+I4*C34-R4*S34+
     .I5*C35-R5*S35
      X(J4)=R1*C41+I1*S41+R2*C42+I2*S42+R3*C43+I3*S43+R4*C44+I4*S44+
     .R5*C45+I5*S45
      Y(J4)=I1*C41-R1*S41+I2*C42-R2*S42+I3*C43-R3*S43+I4*C44-R4*S44+
     .I5*C45-R5*S45
      X(J5)=R1*C51+I1*S51+R2*C52+I2*S52+R3*C53+I3*S53+R4*C54+I4*S54+
     .R5*C55+I5*S55
      Y(J5)=I1*C51-R1*S51+I2*C52-R2*S52+I3*C53-R3*S53+I4*C54-R4*S54+
     .I5*C55-R5*S55
 1100 CONTINUE
 1200 CONTINUE
      GO TO 1000
 1300 CONTINUE
      IF (M.LE.1) GO TO 2400
C
C     GENERAL FACTORS
C
      DO 1400 J=2,PMAX
      P=J
      IF (M.EQ.(M/P)*P) GO TO 1500
 1400 CONTINUE
      CALL FCT ERR
 1500 CONTINUE
      JT=(P-1)**2+1
C
C     SET UP ARBITRARY FACTORS
C
      DO 1600 J=1,JT
      ARG=TWOPI*FLOAT(J-1)/FLOAT(P)
      A(J)=COS(ARG)
      B(J)=SIN(ARG)
 1600 CONTINUE
      MR=M
      M=M/P
      DO 2300 J=1,M
      ARG=TWOPI*FLOAT(J-1)/FLOAT(MR)
C
C     ABSORB TWIDDLE FACTOR INTO ANALYSIS COEFFICIENTS
C
      DO 1800 U=1,P
      C(U,1)=COS(FLOAT(U-1)*ARG)
      S(U,1)=SIN(FLOAT(U-1)*ARG)
      DO 1700 V=2,P
      JT=(U-1)*(V-1)+1
      C(U,V)=C(U,1)*A(JT)-S(U,1)*B(JT)
      S(U,V)=C(U,1)*B(JT)+S(U,1)*A(JT)
 1700 CONTINUE
 1800 CONTINUE
      DO 2200 K=MR,NOPTS,MR
C
C     GENERAL ANALYSIS
```

```
C
      DO 1900 U=1,P
      JT=J+K-MR+(U-1)*M
      R(U)=X(JT)
      I(U)=Y(JT)
 1900 CONTINUE
      DO 2100 U=1,P
      XT=0.0
      YT=0.0
      DO 2000 V=1,P
      XT=XT+R(V)*C(U,V)+I(V)*S(U,V)
      YT=YT+I(V)*C(U,V)-R(V)*S(U,V)
 2000 CONTINUE
      JT=J+K-MR+(U-1)*M
      X(JT)=XT
      Y(JT)=YT
 2100 CONTINUE
 2200 CONTINUE
 2300 CONTINUE
      GO TO 1300
 2400 CONTINUE
      RETURN
      END
      SUBROUTINE SORT 1D
C     UNSCRAMBLING PROGRAM FOR ONE DIMENSIONAL FOURIER COEFFICIENTS
C
      COMMON/DAT/X(3000),Y(3000)
      COMMON/CONST/NOPTS
      REAL  S(3000)
C
      INTEGER JT
      INTEGER DO,LIM(13),STEP(13),P,PMAX
      INTEGER A,B,C,D,E,F,G,H,I,J,K,L,M,AL,BL,CL,DL,EL,FL,GL,HL,IL,JL,
     .KL,LL,ML,AS,BS,CS,DS,ES,FS,GS,HS,IS,JS,KS,LS,MS
C
C     DIGIT REVERSER FOR USE WITH FOUR 1D . S MUST BE THE SAME SIZE AS
C     X AND Y.
C
C     EQUIVALENCES TO ALLOW INDEXING TO SET PARAMETERS AND ALLOW
C     SCALARS FOR USE IN THE DO LOOPS.
C
      EQUIVALENCE (AS,STEP(1)),(BS,STEP(2)),(CS,STEP(3)),(DS,STEP(4)),
     .(ES,STEP(5)),(FS,STEP(6)),(GS,STEP(7)),(HS,STEP(8)),(IS,STEP(9)),
     .(JS,STEP(10)),(KS,STEP(11)),(LS,STEP(12)),(MS,STEP(13))
      EQUIVALENCE (AL,LIM(1)),(BL,LIM(2)),(CL,LIM(3)),(DL,LIM(4)),
     .(EL,LIM(5)),(FL,LIM(6)),(GL,LIM(7)),(HL,LIM(8)),(IL,LIM(9)),
     .(JL,LIM(10)),(KL,LIM(11)),(LL,LIM(12)),(ML,LIM(13))
C
C     PMAX IS SET TO AGREE WITH FOUR 1D
C
      PMAX=13
C
C     SET LIMITS AND STEP SIZES FROM INNER LOOPS GOING OUT
C
      DO=13
      M=NOPTS
  100 CONTINUE
C
C     CHECK FOR FACTORS OF 4
C
```

```
      IF (M.NE.(M/4)*4) GO TO 200
      M=M/4
C
C     REALLY WANT 0-4*M-1 BUT WE GO FROM 1 TO 4*M.  4 STEPS OF M WITH
C     MAXIMUM DISPLACEMENT OF M INITIALLY
C
      LIM(DO)=4*M
      STEP(DO)=M
      DO=DO-1
      GO TO 100
  200 CONTINUE
C
C     CHECK FOR REMAINING FACTORS
C
      IF (M.LE.1) GO TO 500
C
C     FACTORS OF 2,3,5,7,11,13
C
      DO 300 JT=2,PMAX
      P=JT
      IF (M.EQ.(M/P)*P) GO TO 400
  300 CONTINUE
C
C     ERROR EXIT IF FACTORS ABOVE PMAX ARE NEEDED
C
      CALL FCT ERR
  400 CONTINUE
      M=M/P
C
C     REALLY WANT 0-P*M-1 BUT WE USE 1 TO P*M.  P STEPS OF M WITH
C     MAXIMUM INITIAL DISPLACEMENT OF M
C
      LIM(DO)=P*M
      STEP(DO)=M
      DO=DO-1
      GO TO 200
  500 CONTINUE
C
C     FINISH OUT THE DO LOOPS TO MAKE OUTER LOOPS EXECUTE ONLY ONCE
C
      DO 600 JT=1,DO
      LIM(JT)=1
      STEP(JT)=1
  600 CONTINUE
C
C     SET JT SO THAT JT RUNS FROM 1 TO NOPTS  IN STEPS OF 1 WHILE M WILL
C     RUN WITH REVERSED DIGITS
C
      JT=0
      DO 700 A=1,AL,AS
      DO 700 B=A,BL,BS
      DO 700 C=B,CL,CS
      DO 700 D=C,DL,DS
      DO 700 E=D,EL,ES
      DO 700 F=E,FL,FS
      DO 700 G=F,GL,GS
      DO 700 H=G,HL,HS
      DO 700 I=H,IL,IS
      DO 700 J=I,JL,JS
      DO 700 K=J,KL,KS
```

```
      DO 700 L=K,LL,LS
      DO 700 M=L,ML,MS
      JT=JT+1
      S(JT)=X(M)
  700 CONTINUE
C
C     COPY BACK OUT OF THE SCRATCH ARRAY
C
      DO 800 JT=1,NOPTS
      X(JT)=S(JT)
  800 CONTINUE
C
      JT=0
      DO 900 A=1,AL,AS
      DO 900 B=A,BL,BS
      DO 900 C=B,CL,CS
      DO 900 D=C,DL,DS
      DO 900 E=D,EL,ES
      DO 900 F=E,FL,FS
      DO 900 G=F,GL,GS
      DO 900 H=G,HL,HS
      DO 900 I=H,IL,IS
      DO 900 J=I,JL,JS
      DO 900 K=J,KL,KS
      DO 900 L=K,LL,LS
      DO 900 M=L,ML,MS
      JT=JT+1
      S(JT)=Y(M)
  900 CONTINUE
C
C     COPY BACK OUT OF THE SCRATCH ARRAY
C
      DO 950 JT=1,NOPTS
      Y(JT)=S(JT)
  950 CONTINUE
      RETURN
      END
      SUBROUTINE FCT ERR
C     FACTORING ERROR
C
C     FACTORING ERROR IN FOUR 1D OR SORT 1D.
C
C     CURRENTLY TAKEN IF A FACTOR ABOVE 13 IS REQUIRED.  (THE ARRAYS
C     ARE NOT BIG ENOUGH TO HANDLE THINGS ABOVE 13.)
C
      WRITE (6,100)
      CALL EXIT
  100 FORMAT (1X,15HFACTORING ERROR)
      RETURN
      END
```

Program 2

Main programs and subroutines for computing a two-dimensional Fourier transform of a digital matrix that is in either the distance or the frequency domain.

The primary program transforms a space domain digital matrix into the frequency domain, then carries out the inverse transform back to the space domain.

The input to the program is:

Format (5X, 15)	-	input device
Format (5X,F8.3)	-	digital interval in miles
Format (5X,315)	-	number of rows; number of columns; zero
Format (5X,15F4.0)	-	input is a continuous vector e.g. for the matrix I(11) I(12) I(13) I(21) I(22) I(23) I(31) I(32) I(33)

input order is
I(22) I(23) I(21) I(32) I(33)
I(31) I(12) I(13) I(11)

Output is in the same order as the input and includes the real and imaginary amplitudes, absolute amplitude, power and phase.

```
C       THIS PROGRAM CALCULATES A TWO DIMENSIONAL FOURIER TRANSFORM USING
C       AN ALGORITHM OF GOOD(1958) AS MODIFIED BY COOLEY-TUKEY(1966) AND
C       GENTLEMAN-SANDE(1966)
C
C       X(J) IS THE REAL INPUT VECTOR IN SPACE DOMAIN.
C       FOR COMPUTATION PROGRAM USES X(J)+IY(J  WHERE Y(J)=0.0
C       OUTPUT RESULTS ARE GIVEN AS X(J)+IY(J) IN FREQUENCY DOMAIN
C       N(J,K,0)  ***  ARRAY OF DATA IS TWO DIMENSIONAL WITH SIDE J BY K.
C       NOPTS    ***   NUMBER OF DATA POINTS  (J*K).
C       DELT   ***   THE DIGITIZING INTERVAL IN MILES.
C
        COMMON/DAT/X(6000).Y(6000)
        COMMON/CONST/N(3).NOPTS
     10 FORMAT (5X,I5)
     20 FORMAT (5X,3I5)
     30 FORMAT (5X,F8.3)
     35 FORMAT  (5X,15F4.0)
     36 FORMAT(1X,10F13.4)
     45 FORMAT (1HJ)
     40 FORMAT(1HJ,60X,10HINPUT DATA)
     42 FORMAT(1HT,60X,10H**********)
     50 FORMAT(1HT,25X,80H***********************************************
       1*********************************)
     60 FORMAT(1X,6HDELT =.F8.3,8X,18HNYQUIST FREQUENCY=,F8.3)
     70 FORMAT(1HJ,22X.15HFREQUENCY =2*J*,F10.6,1X,15HCYCLES PER MILE)
    100 FORMAT(1H1,49X,33HTWO DIMENSIONAL FOURIER TRANSFORM)
    110 FORMAT(1HT,49X,33H*********************************)
    120 FORMAT(5X,1HJ, 9X,3HROW,6X,6HCOLUMN,6X,10HREAL(FREQ), 9X,15HIMAGIN
       1ARY(FREQ),10X,7HMODULUS,13X,10HFULL POWER,13X,5HPHASE)
    125 FORMAT(4X,3H***,8X,3H***,6X,6H******,6X,10H**********, 9X,15H*****
       1**********,10X,7H*******,13X,10H**********,13X,5H*****)
    130 FORMAT(1X,I5,6X,I5,6X,I5,7X,1PE11.4,11X,1PE11.4,10X,1PE11.4,10X,1P
       1E11.4,10X,1PE11.4)
    310 FORMAT(1H1,45X,41HTWO DIMENSIONAL INVERSE FOURIER TRANSFORM)
    315 FORMAT(46X,41H*****************************************)
    320 FORMAT(1HL,56X,17HREAL (SPACE) PART)
    325 FORMAT(1HT,56X,17H*****************)
        READ (5,10) INPUT
        READ (5,30) DELT
        READ (5,20) (N(J),J=1.3)
        NOPTS = N(1)*N(2)
        READ (INPUT,35) (X(J),J=1,NOPTS)
        WRITE (6,40)
        WRITE(6,42)
        NN=N(1)
        NNN=N(2)
        K=1
        L=0
        DO 80 M=1,NN
        L=L+N(2)
        WRITE (6,36) (X(J),J=K,L)
        WRITE (6,45)
        K=L+1
     80 CONTINUE
        WRITE (6,50)
        FN = 1./(2.*DELT)
        WRITE (6,60) DELT,FN
        FP = FN/(FLOAT(NOPTS))
        WRITE (6,70) FP
        DO 90 J=1,NOPTS
```

```
      Y(J) = 0.0
   90 CONTINUE
      CALL  FOUR MD
      CALL  SORT MD
      J=0
      DO 400 J5=1,NOPTS
      J=J+1
      X(J)=X(J)/FLOAT(NOPTS)
      Y(J)=Y(J)/FLOAT(NOPTS)
  400 CONTINUE
      WRITE (6,100)
      WRITE (6,110)
      WRITE (6,120)
      WRITE(6,125)
      J = 0
C     FOURIER TRANSFORM ARRAY IS WRITTEN OUT BY COLUMNS.
      DO 140 KK=1,NN
      DO 140 JJ=1,NNN
      J = J+1
      C=X(J)
      D=Y(J)
      AMPL=SQRT(C**2+D**2)
      IF(J.NE.1) GO TO 292
      POWER=AMPL*AMPL
      GO TO 293
  292 POWER=2.0*AMPL*AMPL
  293 IF(C.LE.0.001) GO TO 210
      FTAN=ATAN2(D,C)
      PHASE=180.0*FTAN/3.14159
      GO TO 240
  210 PHASE=90.0
  240 IF ((NNN+1)/2-JJ) 121,122,122
  122 JR=JJ-1
      IF ((NN+1)/2-KK)  123,124,124
  124 KC=KK-1
      GO TO 127
  123 KC=KK-NN-1
      GO TO 127
  121 IF ((NN+1)/2-KK) 126,128,128
  128 KC=KK-1
      JR=JJ-NNN-1
      GO TO 127
  126 KC=KK-NN-1
      JR=JJ-NNN-1
  127 WRITE (6,130) J,JR.KC,X(J),Y(J),AMPL,POWER,PHASE
  140 CONTINUE
      J=0
      DO 250 J3=1,NOPTS
      J=J+1
C     REPLACE FOURIER COEFFICIENTS BY COMPLEX  CONJUGATE.
      F=Y(J)
      Y(J)=-F
  250 CONTINUE
      CALL FOUR MD
      CALL SORT MD
      J=0
      DO 350 J4=1,NOPTS
      J=J+1
C     TAKE COMPLEX CONJUGATE.
      GG=Y(J)
```

```
      Y(J)=-GG
  350 CONTINUE
      WRITE (6,310)
      WRITE (6,315)
      WRITE (6,320)
      WRITE (6,325)
      K=1
      L=0
      DO 260 M=1,NN
      L=L+N(2)
      WRITE(6,36) (X(J),J=K,L)
      WRITE(6,45)
      K=L+1
  260 CONTINUE
      WRITE(6,261)
  261 FORMAT(1H1,55X,21HIMAGINARY(SPACE) PART)
      WRITE(6,262)
  262 FORMAT(1HT,55X,21H*********************)
      K=1
      L=0
      DO 263 M=1,NNN
      L=L+N(1)
      WRITE(6,36) (Y(J),J=K,L)
      WRITE(6,45)
      K=L+1
  263 CONTINUE
      STOP
      END
```

This program is a short version of the general main program and computes the distance domain transform of a two-dimensional frequency domain, zero phase filter.

Input format is the same as for the general program and output is the distance domain amplitude.

```
C       THIS PROGRAM CALCULATES A TWO DIMENSIONAL FOURIER TRANSFORM USING
C       AN ALGORITHM OF GOOD(1958) AS MODIFIED BY COOLEY-TUKEY(1966) AND
C       GENTLEMAN-SANDE(1966)
C
C       X(J) IS THE REAL ZERO PHASE INPUT VECTOR IN THE FREQUENCY DOMAIN
C       N(J,K,0)  ***  ARRAY OF DATA IS TWO DIMENSIONAL WITH SIDE J BY K.
C       NOPTS    ***   NUMBER OF DATA POINTS  (J*K).
C       DELT    ***    THE DIGITIZING INTERVAL IN MILES.
C
        COMMON/DAT/X(6000),Y(6000)
        COMMON/CONST/N(3),NOPTS
     10 FORMAT (5X,I5)
     20 FORMAT (5X,3I5)
     30 FORMAT (5X,F8.3)
     35 FORMAT  (5X,15F4.0)
     36 FORMAT(1X,10F13.4)
     45 FORMAT (1HJ)
     40 FORMAT(1HJ,60X,10HINPUT DATA)
     42 FORMAT(1HT,60X,10H**********)
     50 FORMAT(1HT,25X,80H**********************************************
       1**********************************)
     60 FORMAT(1X,6HDELT =,F8.3,8X,18HNYQUIST FREQUENCY=,F8.3)
     70 FORMAT(1HJ,22X,15HFREQUENCY =2*J*,F10.6,1X,15HCYCLES PER MILE)
        READ (5,10) INPUT
        READ (5,30) DELT
        READ (5,20) (N(J),J=1,3)
        NOPTS = N(1)*N(2)
        READ (INPUT,35) (X(J),J=1,NOPTS)
        WRITE (6,40)
        WRITE(6,42)
        NN=N(1)
        NNN=N(2)
        K=1
        L=0
        DO 80 M=1,NN
        L=L+N(2)
        WRITE (6,36) (X(J),J=K,L)
        WRITE (6,45)
        K=L+1
     80 CONTINUE
        WRITE (6,50)
        FN = 1./(2.*DELT)
        WRITE (6,60) DELT,FN
        FP = FN/(FLOAT(NOPTS))
        WRITE (6,70) FP
        DO 90 J=1,NOPTS
        Y(J) = 0.0
     90 CONTINUE
        CALL  FOUR MD
        CALL  SORT MD
        K=1
        L=0
        DO 260 M=1,NN
        L=L+N(2)
        WRITE(6,36) (X(J),J=K.L)
        WRITE(6,45)
        K=L+1
    260 CONTINUE
        STOP
        END
```

Subroutines for the two-dimensional Fast Fourier transform program.

```
      SUBROUTINE FOUR MD
C
C     TWO-DIMENSIONAL FOURIER TRANSFORM
C
      COMMON/DAT/X(6000),Y(6000)
      COMMON/CONST/N(3),NOPTS
C
C     NEED SUBROUTINE SORT MD  TO UNSCAMBLE FOURIER COEFFICIENTS
C
      REAL I1,I2,I3,I4,I5
      INTEGER P,PMAX,PROD,SC,U,V
C     REAL I (PMAX), R (PMAX), C (PMAX,PMAX), S (PMAX,PMAX),
C    .A ((PMAX-1)**2+1), B ((PMAX-1)**2+1)
      REAL I (19), R (19), C (19,19), S (19,19), A (325), B (325)
C
C     THIS SUBROUTINE CAUSES X(J1 J2 ...) + IY(J1 J2 ... ) TO BE REPLACED
C     BY THEIR FOURIER TRANSFORM WHEN X+(F1 F2 ...)+IY+(F1 F2 ...)=
C     SUM T1=0,N1-1OF  SUM T2=0,N2-1OF ... X(T1 T2 ...)PIY(T1 T2 ...)
C     F(-F1.T1/N1).F(-F2.T2/N2) ...
C     WHERE JJ=TJ+1=FJ+1 AND NJ=N(J)
C
C     N(K+1)=0 INDICATES THAT THERE ARE ONLY K DIMENSIONS
C     X(J1 J2 ...) IS STORED AT TK.N(K-1 ... .N1+ +T3.N2.N1+T2.N1+T1
C
C     SEE COMMENT IN GR 1D FT
C     M/SC PLAYS THE SAME ROLE HERE AS DOES M IN GR 1D FT.  SC IS USED TO
C     ''STEP'' OVER THE OTHER DIMENSIONS. EACH DIMENSION IS DONE INDEPENDEN
C
      PMAX=19
C
      TWOPI=6.283185307
      PROD=1
      ND=1
  100 CONTINUE
      PROD=PROD*N(ND)
      ND=ND+1
      IF (N(ND).GT.0) GO TO 100
      ND=1
      M=PROD
      SC=PROD
  200 CONTINUE
      SC=SC/N(ND)
      ND=ND+1
  300 CONTINUE
      IF (M/SC.NE.(M/SC/4)*4) GO TO 600
      MR=M
      M=M/4
      DO 500 J=1,M
      ARG=TWOPI*FLOAT((J-1)/SC)/FLOAT(MR/SC)
      C1=COS(ARG)
      S1=SIN(ARG)
      C2=COS(2.0*ARG)
      S2=SIN(2.0*ARG)
      C3=COS(3.0*ARG)
      S3=SIN(3.0*ARG)
      DO 400 K=MR,PROD,MR
      J1=J+K-MR
      J2=J1+M
      J3=J2+M
      J4=J3+M
```

```
      R1=X(J1)+X(J3)
      R2=X(J1)-X(J3)
      I1=Y(J1)+Y(J3)
      I2=Y(J1)-Y(J3)
      R3=X(J2)+X(J4)
      R4=X(J2)-X(J4)
      I3=Y(J2)+Y(J4)
      I4=Y(J2)-Y(J4)
      X(J1)=R1+R3
      Y(J1)=I1+I3
      X(J2)=(R2+I4)*C1+(I2-R4)*S1
      Y(J2)=(I2-R4)*C1-(R2+I4)*S1
      X(J3)=(R1-R3)*C2+(I1-I3)*S2
      Y(J3)=(I1-I3)*C2-(R1-R3)*S2
      X(J4)=(R2-I4)*C3+(I2+R4)*S3
      Y(J4)=(I2+R4)*C3-(R2-I4)*S3
  400 CONTINUE
  500 CONTINUE
      GO TO 300
  600 CONTINUE
      IF (M/SC.NE.(M/SC/2)*2) GO TO 900
      MR=M
      M=M/2
      DO 800 J=1,M
      ARG=TWOPI*FLOAT((J-1)/SC)/FLOAT(MR/SC)
      C1=COS(ARG)
      S1=SIN(ARG)
      DO 700 K=MR,PROD,MR
      J1=J+K-MR
      J2=J1+M
      R1=X(J1)+X(J2)
      R2=X(J1)-X(J2)
      I1=Y(J1)+Y(J2)
      I2=Y(J1)-Y(J2)
      X(J1)=R1
      Y(J1)=I1
      X(J2)=R2*C1+I2*S1
      Y(J2)=I2*C1-R2*S1
  700 CONTINUE
  800 CONTINUE
      GO TO 600
  900 CONTINUE
      IF (M/SC.NE.(M/SC/3)*3) GO TO 1200
      MR=M
      M=M/3
      A1=COS(TWOPI/3.0)
      B1=SIN(TWOPI/3.0)
      A2=COS(2.0*TWOPI/3.0)
      B2=SIN(2.0*TWOPI/3.0)
      DO 1100 J=1,M
      ARG=TWOPI*FLOAT((J-1)/SC)/FLOAT(MR/SC)
      C21=COS(ARG)
      S21=SIN(ARG)
      C22=C21*A1-S21*B1
      S22=C21*B1+S21*A1
      C23=C21*A2-S21*B2
      S23=C21*B2+S21*A2
      C31=COS(2.0*ARG)
      S31=SIN(2.0*ARG)
      C32=C31*A2-S31*B2
```

```
      S32=C31*B2+S31*A2
      C33=C31*A1-S31*B1
      S33=C31*B1+S31*A1
      DO 1000 K=MR,PROD,MR
      J1=J+K-MR
      J2=J1+M
      J3=J2+M
      R1=X(J1)
      I1=Y(J1)
      R2=X(J2)
      I2=Y(J2)
      R3=X(J3)
      I3=Y(J3)
      X(J1)=R1+R2+R3
      Y(J1)=I1+I2+I3
      X(J2)=R1*C21+I1*S21+R2*C22+I2*S22+R3*C23+I3*S23
      Y(J2)=I1*C21-R1*S21+I2*C22-R2*S22+I3*C23-R3*S23
      X(J3)=R1*C31+I1*S31+R2*C32+I2*S32+R3*C33+I3*S33
      Y(J3)=I1*C31-R1*S31+I2*C32-R2*S32+I3*C33-R3*S33
 1000 CONTINUE
 1100 CONTINUE
      GO TO 900
 1200 CONTINUE
      IF (M/SC.NE.(M/SC/5)*5) GO TO 1500
      MR=M
      M=M/5
      A1=COS(TWOPI/5.0)
      B1=SIN(TWOPI/5.0)
      A2=COS(2.0*TWOPI/5.0)
      B2=SIN(2.0*TWOPI/5.0)
      A3=COS(3.0*TWOPI/5.0)
      B3=SIN(3.0*TWOPI/5.0)
      A4=COS(4.0*TWOPI/5.0)
      B4=SIN(4.0*TWOPI/5.0)
      DO 1400 J=1,M
      ARG=TWOPI*FLOAT((J-1)/SC)/FLOAT(MR/SC)
      C21=COS(ARG)
      S21=SIN(ARG)
      C22=C21*A1-S21*B1
      S22=C21*B1+S21*A1
      C23=C21*A2-S21*B2
      S23=C21*B2+S21*A2
      C24=C21*A3-S21*B3
      S24=C21*B3+S21*A3
      C25=C21*A4-S21*B4
      S25=C21*B4+S21*A4
      C31=COS(2.0*ARG)
      S31=SIN(2.0*ARG)
      C32=C31*A2-S31*B2
      S32=C31*B2+S31*A2
      C33=C31*A4-S31*B4
      S33=C31*B4+S31*A4
      C34=C31*A1-S31*B1
      S34=C31*B1+S31*A1
      C35=C31*A3-S31*B3
      S35=C31*B3+S31*A3
      C41=COS(3.0*ARG)
      S41=SIN(3.0*ARG)
      C42=C41*A3-S41*B3
      S42=C41*B3+S41*A3
```

```
      C43=C41*A1-S41*B1
      S43=C41*B1+S41*A1
      C44=C41*A4-S41*B4
      S44=C41*B4+S41*A4
      C45=C41*A2-S41*B2
      S45=C41*B2+S41*A2
      C51=COS(4.0*ARG)
      S51=SIN(4.0*ARG)
      C52=C51*A4-S51*B4
      S52=C51*B4+S51*A4
      C53=C51*A3-S51*B3
      S53=C51*B3+S51*A3
      C54=C51*A2-S51*B2
      S54=C51*B2+S51*A2
      C55=C51*A1-S51*B1
      S55=C51*B1+S51*A1
      DO 1300 K=MR,PROD,MR
      J1=J+K-MR
      J2=J1+M
      J3=J2+M
      J4=J3+M
      J5=J4+M
      R1=X(J1)
      I1=Y(J1)
      R2=X(J2)
      I2=Y(J2)
      R3=X(J3)
      I3=Y(J3)
      R4=X(J4)
      I4=Y(J4)
      R5=X(J5)
      I5=Y(J5)
      X(J1)=R1+R2+R3+R4+R5
      Y(J1)=I1+I2+I3+I4+I5
      X(J2)=R1*C21+I1*S21+R2*C22+I2*S22+R3*C23+I3*S23+R4*C24+I4*S24+
     .R5*C25+I5*S25
      Y(J2)=I1*C21-R1*S21+I2*C22-R2*S22+I3*C23-R3*S23+I4*C24-R4*S24+
     .I5*C25-R5*S25
      X(J3)=R1*C31+I1*S31+R2*C32+I2*S32+R3*C33+I3*S33+R4*C34+I4*S34+
     .R5*C35+I5*S35
      Y(J3)=I1*C31-R1*S31+I2*C32-R2*S32+I3*C33-R3*S33+I4*C34-R4*S34+
     .I5*C35-R5*S35
      X(J4)=R1*C41+I1*S41+R2*C42+I2*S42+R3*C43+I3*S43+R4*C44+I4*S44+
     .R5*C45+I5*S45
      Y(J4)=I1*C41-R1*S41+I2*C42-R2*S42+I3*C43-R3*S43+I4*C44-R4*S44+
     .I5*C45-R5*S45
      X(J5)=R1*C51+I1*S51+R2*C52+I2*S52+R3*C53+I3*S53+R4*C54+I4*S54+
     .R5*C55+I5*S55
      Y(J5)=I1*C51-R1*S51+I2*C52-R2*S52+I3*C53-R3*S53+I4*C54-R4*S54+
     .I5*C55-R5*S55
 1300 CONTINUE
 1400 CONTINUE
      GO TO 1200
 1500 CONTINUE
      IF (M/SC.LE.1) GO TO 2600
      DO 1600 J=2,PMAX
      P=J
      IF (M/SC.EQ.(M/SC/P)*P) GO TO 1700
 1600 CONTINUE
      CALL FCT ERR
```

```
 1700 CONTINUE
      JT=(P-1)**2+1
      DO 1800 J=1,JT
      ARG=TWOPI*FLOAT(J-1)/FLOAT(P)
      A(J)=COS(ARG)
      B(J)=SIN(ARG)
 1800 CONTINUE
      MR=M
      M=M/P
      DO 2500 J=1,M
      ARG=TWOPI*FLOAT((J-1)/SC)/FLOAT(MR/SC)
      DO 2000 U=1,P
      C(U,1)=COS(FLOAT(U-1)*ARG)
      S(U,1)=SIN(FLOAT(U-1)*ARG)
      DO 1900 V=2,P
      JT=(U-1)*(V-1)+1
      C(U,V)=C(U,1)*A(JT)-S(U,1)*B(JT)
      S(U,V)=C(U,1)*B(JT)+S(U,1)*A(JT)
 1900 CONTINUE
 2000 CONTINUE
      DO 2400 K=MR,PROD,MR
      DO 2100 U=1,P
      JT=J+K-MR+(U-1)*M
      R(U)=X(JT)
      I(U)=Y(JT)
 2100 CONTINUE
      DO 2300 U=1,P
      XT=0.0
      YT=0.0
      DO 2200 V=1,P
      XT=XT+R(V)*C(U,V)+I(V)*S(U,V)
      YT=YT+I(V)*C(U,V)-R(V)*S(U,V)
 2200 CONTINUE
      JT=J+K-MR+(U-1)*M
      X(JT)=XT
      Y(JT)=YT
 2300 CONTINUE
 2400 CONTINUE
 2500 CONTINUE
      GO TO 1500
 2600 CONTINUE
      IF (N(ND).GT.0) GO TO 200
      RETURN
      END
      SUBROUTINE SORT MD
C
C     TWO DIMENSIONAL FOURIER SORT TO UNSCRAMBLE THE FOURIER COEFFICIENT
C
      COMMON/DAT/X(6000),Y(6000)
      COMMON/CONST/N(3),NOPTS
      REAL   S(6000)
C
      INTEGER ND,JT,IT
      INTEGER DO,SC,LIM(19),STEP(19),P,PMAX
      INTEGER A,B,C,D,E,F,G,H,I,J,K,L,M,Q,R,T,U,V,W,AL,BL,CL,DL,EL,FL,GL
     .,HL,IL,JL,KL,LL,ML,QL,RL,TL,UL,VL,WL, AS,BS,CS,DS,ES,FS,GS,HS,IS,J
     .S,KS,LS,MS,QS,RS,TS,US,VS,WS
C
C     SEE ALL THE COMMENTS IN GR 1D FS
C
```

```
      EQUIVALENCE (AS,STEP(1)),(BS,STEP(2)),(CS,STEP(3)),(DS,STEP(4)),
     .(ES,STEP(5)),(FS,STEP(6)),(GS,STEP(7)),(HS,STEP(8)),(IS,STEP(9)),
     .(JS,STEP(10)),(KS,STEP(11)),(LS,STEP(12)),(MS,STEP(13)),(QS,STEP(1
     .4)),(RS,STEP(15)),(TS,STEP(16)),(US,STEP(17)),(VS,STEP(18)),(WS,ST
     .EP(19))
      EQUIVALENCE (AL,LIM(1)),(BL,LIM(2)),(CL,LIM(3)),(DL,LIM(4)),
     .(EL,LIM(5)),(FL,LIM(6)),(GL,LIM(7)),(HL,LIM(8)),(IL,LIM(9)),
     .(JL,LIM(10)),(KL,LIM(11)),(LL,LIM(12)),(ML,LIM(13)),
     .(QL,LIM(14)),(RL,LIM(15)),(TL,LIM(16)),(UL,LIM(17)),(VL,LIM(18)),
     .(WL,LIM(19))
C
C     DIGIT REVERSER FOR USE WITH GR MD FT.
C
C     WE REVERSE THE DIGITS INSIDE EACH DIMENSION.  WE REALLY DO USE
C     RANGES OF 0-(P-1)*M FOR THE DO LOOPS.  SC IS THE FACTOR USED TO
C     'STEP' OVER PREVIOUS DIMENSIONS
C
      PMAX=19
      DO=19
      ND=1
      SC=1
  100 CONTINUE
      M=N(ND)
  200 CONTINUE
      IF (M.NE.(M/4)*4) GO TO 300
      M=M/4
C
C     0,M*SC,2*M*SC,3*M*SC
C
      LIM(DO)=3*M*SC
      STEP(DO)=M*SC
      DO=DO-1
      GO TO 200
  300 CONTINUE
      IF (M.LE.1) GO TO 600
      DO 400 JT=2,PMAX
      P=JT
      IF (M.EQ.(M/P)*P) GO TO 500
  400 CONTINUE
      CALL FCT ERR
  500 CONTINUE
      M=M/P
C
C     0.M*SC,2*M*SC, ... ,(P-1)*M*SC
C
      LIM(DO)=(P-1)*M*SC
      STEP(DO)=M*SC
      DO=DO-1
      GO TO 300
  600 CONTINUE
C
C     TEST TO SEE IF ANOTHER DIMENSION.  GO BACK AFTER SETTING SC IF SO.
C
      SC=SC*N(ND)
      ND=ND+1
      IF (N(ND).GT.0) GO TO 100
      DO 700 JT=1,DO
      LIM(JT)=0
      STEP(JT)=1
  700 CONTINUE
```

```
      JT=0
      DO 800 A=0,AL,AS
      DO 800 B=0,BL,BS
      DO 800 C=0,CL,CS
      DO 800 D=0,DL,DS
      DO 800 E=0,EL,ES
      DO 800 F=0,FL,FS
      DO 800 G=0,GL,FS
      DO 800 H=0,HL,HS
      DO 800 I=0,IL,IS
      DO 800 J=0,JL,JS
      DO 800 K=0,KL,KS
      DO 800 L=0,LL,LS
      DO 800 M=0,ML,MS
      DO 800 Q=0,QL,QS
      DO 800 R=0,RL,RS
      DO 800 T=0,TL,TS
      DO 800 U=0,UL,US
      DO 800 V=0,VL,VS
      DO 800 W=0,WL,WS
      JT=JT+1
      IT=A+B+C+D+E+F+G+H+I+J+K+L+M+Q+R+T+U+V+W+1
      S(JT)=X(IT)
  800 CONTINUE
      DO 900 JT=1.SC
      X(JT)=S(JT)
  900 CONTINUE
C
      JT=0
      DO 950 A=0,AL,AS
      DO 950 B=0,BL,BS
      DO 950 C=0,CL,CS
      DO 950 D=0,DL,DS
      DO 950 E=0,EL,ES
      DO 950 F=0,FL,FS
      DO 950 G=0,GL,FS
      DO 950 H=0,HL,HS
      DO 950 I=0,IL,IS
      DO 950 J=0,JL,JS
      DO 950 K=0,KL,KS
      DO 950 L=0,LL,LS
      DO 950 M=0,ML,MS
      DO 950 Q=0,QL,QS
      DO 950 R=0,RL,RS
      DO 950 T=0,TL,TS
      DO 950 U=0,UL,US
      DO 950 V=0,VL,VS
      DO 950 W=0,WL,WS
      JT=JT+1
      IT=A+B+C+D+E+F+G+H+I+J+K+L+M+Q+R+T+U+V+W+1
      S(JT)=Y(IT)
  950 CONTINUE
C
      DO 975 JT=1,SC
      Y(JT)=S(JT)
  975 CONTINUE
      RETURN
      END
      SUBROUTINE FCT ERR
C     FACTORING ERROR
```

```
C
C     FACTORING ERROR IN GR  1D OR MD  FT OR FS.
C
C     CURRENTLY TAKEN IF A FACTOR ABOVE 19 IS REQUIRED.  (THE ARRAYS
C     ARE NOT BIG ENOUGH TO HANDLE THINGS ABOVE 19.)
C
      WRITE (6,100)
  100 FORMAT (1X,15HFACTORING ERROR)
      CALL EXIT
      RETURN
      END
```

Program 3

This program is a package of integrated subroutines that will carry out all the filtering and mapping routines required in the preparation of the symbolically contoured maps used in this thesis. Maps are input as a continuous digital vector and may be either on cards or on tape. The remainder of the input is a series of cards controlling both the operations on the maps and the form of the output.

Operation control cards are in the form of a subroutine name and one to five arguments. Format (9X,A4,11X,5I4)

Operational control cards are as follows:

SIZE args(1) args(2)

Defines the size of the map, number of rows and number of columns.

CARDS args(1)

Defines the input unit.

TITLE

The two following cards contain the title of the map.

SYMBOL args(1)

Number of levels of contour resolution followed by single card with symbol list.

LIMITS args(1)

Number of specified contour values followed by cards with contour limits and symbols.

FILTER args(1) args(2)

Specifies size of spatial filter followed by cards with filter values. Format (10F8.5)

COMMENT args(1)

The following number of cards appear in the output as a comment.

SEGMENT args(1) args(2) args(3) args(4) args(5)

The numeric map in core is segmented according to specified rows and columns and written on a specified logical unit.

GETNUMERIC args(1)

A numeric map is read into core from logical unit.

CONVOLVE args(1)

The numeric map currently in core is convolved with the filter and is written out on specified logical unit.

AUTO

The current map is symbolically plotted according to the levels and symbols previously specified by "SYMBOL".

GRAPH

Plots the current map according to the values specified in "LIMITS".

CONTOUR args(1)

The current alphabetic map is contoured and written out on the specified logical unit.

GETALPHABETIC args(1)

An alphabetic map is read from specified unit.

PRINT args(1)

The alphabetic map currently in core is automatically segmented where necessary and the specified number of prints are written out.

SPREAD

The current alphabetic map is converted to a one-to-one scale, segmented where necessary, and printed.

PUTALPHABETIC args(1)

Writes the current alphabetic map on specified logical unit.

PUTNUMERIC args(1)

Writes the current numeric map on specified logical unit.

ISOPAK args(1) and args(2)

Computes and reads into core the isopach values between the maps on the specified logical units.

CHUNK args(1) args(2) args(3) args(4) args(5)

Prints a portion of the current alphabetic map according to the specified dimensions and prints the desired number of copies.

HALT

Terminates job.

```
     COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

N 0002               INTEGERTIT(2,20),C(20)
N 0003               REALMAP(212,170),F(50,50)
N 0004               INTEGERNCHRS(50),NNHRS(50)
N 0005               REALXLO(50),XHI(50)
N 0006               INTEGERARGS(5),SIZE,CARDS,SYMBOL,TITLE,LIMITS,COMMEN,AUTO
N 0007               INTEGERPRIN,GRAPH,FILTR,CONV,GETNUM,GETALF,PUTNUM,PUTALF,SETLOG
N 0008               INTEGERHALT,CHUNK,SEGM,CONTR,REWND,SPRED
N 0009               DATASIZE/'SIZE'/
N 0010               DATACARDS/'CARD'/
N 0011               DATASYMBOL/'SYMB'/
N 0012               DATATITLE/'TITL'/
N 0013               DATALIMITS/'LIMI'/
N 0014               DATACOMMEN/'COMM'/
N 0015               DATAAUTO/'AUTO'/
N 0016               DATAPRIN/'PRIN'/
N 0017               DATAGRAPH/'GRAP'/
N 0018               DATAFILTR/'FILT'/
N 0019               DATACONV/'CONV'/
N 0020               DATAGETNUM/'GETN'/
N 0021               DATAPUTNUM/'PUTN'/
N 0022               DATAGETALF/'GETA'/
N 0023               DATAPUTALF/'PUTA'/
N 0024               DATASETLOG/'LOG '/
N 0025               DATAHALT/'HALT'/
N 0026               DATACHUNK/'CHUN'/
N 0027               DATASEGM/'SEGM'/
N 0028               DATACONTR/'CONT'/
N 0029               DATAISOP/'ISOP'/
N 0030               DATAREWND/'REWI'/
N 0031               DATASPRED/'SPRE'/
N 0032               NR=209
N 0033               NC=160
N 0034               NF=50
N 0035               LOG=1
N 0036             1 READ(5,10,END=99)IN,ARGS
N 0037               IF(IN.EQ.SIZE  )GOTO20
N 0039               IF(IN.EQ.CARDS )GOTO21
N 0041               IF(IN.EQ.SYMBOL)GOTO22
N 0043               IF(IN.EQ.TITLE )GOTO23
N 0045               IF(IN.EQ.LIMITS)GOTO24
N 0047               IF(IN.EQ.COMMEN)GOTO26
N 0049               IF(IN.EQ.AUTO  )GOTO28
N 0051               IF(IN.EQ.PRIN  )GOTO29
N 0053               IF(IN.EQ.GRAPH )GOTO31
N 0055               IF(IN.EQ.FILTR )GOTO32
N 0057               IF(IN.EQ.CONV  )GOTO34
N 0059               IF(IN.EQ.GETNUM)GOTO35
N 0061               IF(IN.EQ.GETALF)GOTO36
N 0063               IF(IN.EQ.PUTNUM)GOTO37
N 0065               IF(IN.EQ.PUTALF)GOTO38
N 0067               IF(IN.EQ.SETLOG)GOTO39
N 0069               IF(IN.EQ.HALT  )GOTO40
N 0071               IF(IN.EQ.CHUNK )GOTO41
N 0073               IF(IN.EQ.SEGM  )GOTO43
N 0075               IF(IN.EQ.CONTR )GOTO44
N 0077               IF(IN.EQ.ISOP  )GOTO45
N 0079               IF(IN.EQ.REWND )GOTO47
N 0081               IF(IN.EQ.SPRED )GOTO48
```

```
      WRITE(6,18)IN
      GOTO 1
   20 CONTINUE
      NR=ARGS(1)
      NC=ARGS(2)
      GOTO1
   21 CONTINUE
      IF(ARGS(1).EQ.0)ARGS(1)=5
      CALLCARDIN(MAP,NR,NC,ARGS(1),TIT)
      GOTO1
   22 CONTINUE
      NRES=ARGS(1)
      READ(5,11,END=99)(NCHRS(I),I=1,NRES)
      GOTO1
   23 CONTINUE
      READ(5,17,END=99)TIT
      GOTO1
   24 CONTINUE
      NNES=ARGS(1)
      WRITE(6,102)
      DO25I=1,NNES
      READ(5,12,END=99)XLO(I),XHI(I),NNHRS(I)
   25 WRITE(6,101)XLO(I),XHI(I),NNHRS(I)
      GOTO1
   26 CONTINUE
      IC=ARGS(1)
      WRITE(6,13)
      DO27I=1,IC
      READ(5,17,END=99)C
   27 WRITE(6,14)C
      WRITE(6,15)
      GOTO1
   28 CONTINUE
      CALLPLOT(MAP,NR,NC,NRES,NCHRS,MAP)
      GOTO1
   29 CONTINUE
      IF(ARGS(1).EQ.0)ARGS(1)=1
      NCOPY=ARGS(1)
      DO30I=1,NCOPY
   30 CALLPRYNT(MAP,1,NR,1,NC,TIT,NR,NC)
      GOTO1
   31 CONTINUE
      CALLSET(MAP,NR,NC,NNES,XLO,XHI,NNHRS)
      GOTO1
   32 CONTINUE
      NF=ARGS(1)
      DO33I=1,NF
   33 READ(5,19,END=99)(F(I,J),J=1,NF)
      DO46I=1,NF
   46 WRITE(6,9)(F(I,J),J=1,NF)
      GOTO1
   34 CONTINUE
      CALLCONVOL(MAP,F,NR,NC,NF,ARGS(1))
      GOTO1
   35 CONTINUE
      CALLGETN(MAP,NR,NC,ARGS(1))
      GOTO1
   36 CONTINUE
      CALLGETA(MAP,NR,NC,ARGS(1))
```

```
      GOTO1
   37 CONTINUE
      CALLPUTN(MAP,NR,NC,ARGS(1))
      GOTO1
   38 CONTINUE
      CALLPUTA(MAP,NR,NC,ARGS(1))
      GOTO1
   39 CONTINUE
      LOG=ARGS(1)
      GOTO1
   40 CONTINUE
      STOP
   41 CONTINUE
      IF(ARGS(5).EQ.0)ARGS(5)=1
      NCOPY=ARGS(5)
      DO42I=1,NCOPY
   42 CALLPRYNT(MAP,ARGS(1),ARGS(2),ARGS(3),ARGS(4),TIT,NR,NC)
      GOTO1
   43 CONTINUE
      CALLSEGMEN(MAP,ARGS(1),ARGS(2),ARGS(3),ARGS(4),ARGS(5),NR,NC)
      GOTO1
   44 CONTINUE
      CALLCONTOR(MAP,NR,NC,ARGS(1))
      GOTO1
   45 CONTINUE
      CALLISOPAK(MAP,NR,NC,ARGS(1),ARGS(2))
      GOTO1
   47 CONTINUE
      IDAM=ARGS(1)
      REWIND IDAM
      GOTO1
   48 CONTINUE
      CALLSPREAD(MAP,NR,NC,TIT)
      GOTO1
   99 CONTINUE
      WRITE(6,16)
      STOP
    9 FORMAT(2X,11F8.3)
   10 FORMAT(9X,A4,11X,5I4)
   11 FORMAT(80A1)
   12 FORMAT(5X,2F9.2,5X,A1)
   13 FORMAT('1',24X,82('*'))
   14 FORMAT(25X,'*',20A4,'*')
   15 FORMAT(25X,82('*'))
   16 FORMAT('1',15X,'END OF FILE ENCOUNTERED WHILE READING SYSTEM I
     1 FILE ... JOB TERMINATED')
   17 FORMAT(20A4)
   18 FORMAT(15X,'INSCRUTABLE CONTROL CARD ... ',A4,' ... IGNORED')
   19 FORMAT(10F8.5)
  101 FORMAT(15X,F9.2,10X,F9.2,10X,A1)
  102 FORMAT('1',15X,'L I M I T S'//)
      END

* END OF COMPILATION ******
```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
      SUBROUTINESEGMEN(MAP,NR1,NR2,NC1,NC2,L,NR,NC)
      REALMAP(212,170)
      REWINDL
      DO1 I=1
      DO1I=NR1,NR2
    1 WRITE(L,10)(MAP(I,K),K=NC1,NC2)
      ENDFILE L
      BACKSPACE L
      REWIND L
      RETURN
   10 FORMAT(160F8.3)
      END
```

END OF COMPILATION ******

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
      SUBROUTINE PRYNT(MAP,NR1,NR2,NC1,NC2,TITLE,KR,KC)
      DIMENSIONMAP(212,170),TITLE(2,20)
      NC=NC2-NC1+1
      IF(NC.GT.100)GOTO 99
      CALL PRINT(MAP,NR1,NR2,NC1,NC2,TITLE,KR,KC)
      RETURN
   99 CONTINUE
      III=0
      NC1A=NC1
   61 NC2A=NC1A+99
      IF(NC2A.LE.NC2)GOTO60
      NC2A=NC2
      III=1
   60 CONTINUE
      CALLPRINT(MAP,NR1,NR2,NC1A,NC2A,TITLE,KR,KC)
      IF(NC2A.EQ.NC2)RETURN
      NC1A=NC2A+1
      GOTO61
      END
```

END OF COMPILATION ******

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
      SUBROUTINE PRINT(MAP,NR1,NR2,NC1,NC2,TITLE,KR,KC)
      DIMENSIONMAP(212,170),TITLE(2,20),I(102)
      DIMENSION IND(3,213),JND(3,213),KND(3,213),NOS(10),NL(3)
      DATA IBL/'    '/
      DATA IDOT/'....'/
      DATANOS/'0000111122223333444455556666777788889999'/
      NR=NR2-NR1+1
      NC=NC2-NC1+1
      DO 51 J=1,NC
      IND(1,J)=(NC1+J-1)/100
      IND(2,J)=MOD((NC1+J-1),100)/10
   51 IND(3,J)=  MOD((NC1+J-1),10)
      DO54J=1,NR
      JND(1,J)=(NR1+J-1)/100
      JND(2,J)=MOD((NR1+J-1),100)/10
   54 JND(3,J)=MOD((NR1+J-1),10)
      WRITE(6,10)TITLE
   10 FORMAT(1H1,25X,20A4/26X,20A4//)
      M=(100-NC)/2
      DO1J=1,102
    1 I(J)=IBL
      IMA=1+M
      IMB=1+M+NC+1
      MP1=M+1
      DO 52 J=1,3
      DO53K=1,NC
      KK=IND(J,K)
   53 KND(J,K)=NOS(KK+1)
   52 WRITE(6,12)(I(K),K=1,MP1),(KND(J,K),K=1,NC)
      DO55J=1,3
      DO55K=1,NR
      KK=JND(J,K)
   55 JND(J,K)=NOS(KK+1)
      DO2J=IMA,IMB
    2 I(J)=IDOT
      WRITE(6,11)I
   11 FORMAT(16X,102A1)
      DO3J=NR1,NR2
   12 FORMAT(16X,110A1)
      DO4LL=1,3
    4 NL(LL)=JND(LL,J)
    3 WRITE(6,12)(I(K),K=1,MP1),(MAP(J,K),K=NC1,NC2),IDOT,IBL,NL
      WRITE(6,11)I
      RETURN
      END
```

END OF COMPILATION ******

```
     COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

 0002              SUBROUTINE CONTOR (MAP,NR,NC,L)
 0003              DIMENSIONMAP(212,170)
 0004              INTEGER OUT(170)
 0005              DATA IBL/'    '/
 0006              REWIND L
 0007              NRB=NR-1
 0008              NCB=NC-1
 0009              WRITE(L,10)(MAP(1,J),J=1,NC)
 0010              DO2I=2,NRB
 0011              OUT(1)=MAP(I,1)
 0012              OUT(NC)=MAP(I,NC)
 0013              DO3J=2,NCB
 0014              OUT(J)=MAP(I,J)
 0015              IF(MAP(I,J).NE.MAP(I-1,J))GOTO3
 0017              IF(MAP(I,J).NE.MAP(I+1,J))GOTO3
 0019              IF(MAP(I,J).NE.MAP(I,J+1))GOTO3
 0021              IF(MAP(I,J).NE.MAP(I,J-1))GOTO3
 0023              OUT(J)=IBL
 0024            3 CONTINUE
 0025              WRITE(L,10)(OUT(K),K=1,NC)
 0026            2 CONTINUE
 0027              WRITE(L,10)(MAP(NR,K),K=1,NC)
 0028              ENDFILE L
 0029              BACKSPACE L
 0030              REWIND L
 0031              RETURN
 0032           10 FORMAT(210A1)
 0033              END

 END OF COMPILATION ******
```

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,
0002              SUBROUTINE SELECT(NRES,TEST,XLO,XHI,NCHRS,ICHOS)
0003              DIMENSION XLO(50),XHI(50),NCHRS(50)
0004              DATA IBL/'    '/
0005              ICHOS=IBL
0006              DO 1 I=1,NRES
0007              IT=I
0008              IF(XLO(I).LE.TEST.AND.XHI(I).GE.TEST)GOTO 2
0010            1 CONTINUE
0011              RETURN
0012            2 ICHOS=NCHRS(IT)
0013              RETURN
0014              END
END OF COMPILATION ******
```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
      SUBROUTINE SET(MAP,NR,NC,NRES,XLO,XHI,NCHRS)
      REALMAP(212,170),XLO(50),XHI(50),NCHRS(50)
      DO1I=1,NR
      DO1J=1,NC
    1 CALL SELECT(NRES,MAP(I,J),XLO,XHI,NCHRS,MAP(I,J))
      RETURN
      END
```

END OF COMPILATION ******

```
COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

            SUBROUTINEPLOT(GRID,NR,NC,NRES,NCHARS,MAP)
            INTEGERMAP(212,170)
            INTEGERH(50)
            DIMENSION GRID(212,170),NCHARS(50),P(50)
            DO2I=1,NRES
          2 H(I)=0
            DMAX=0.
            DMIN=100000.
            DO1I=1,NR
            DO1J=1,NC
            IF(GRID(I,J).GT.DMAX)DMAX=GRID(I,J)
            IF(GRID(I,J).LT.DMIN)DMIN=GRID(I,J)
          1 CONTINUE
            DO778I=1,NR
            DO3J=1,NC
            NN=      INT(1.+FLOAT(NRES)*(GRID(I,J)-DMIN)/(DMAX-DMIN))
            H(NN)=H(NN)+1
            MAP (I,J)=NCHARS(NN)
          3 CONTINUE
        778 CONTINUE
            WRITE(6,4)
          4 FORMAT('1',10X,'LEVEL',10X,'     L I M I T S      ',10X,'SYMBOL',
           110X,'INCIDENTS',10X,'PER CENT'///)
            PC=FLOAT(NR*NC)
            XINC=(DMAX-DMIN)/FLOAT(NRES)
            XL=DMIN
            DO5I=1,NRES
            P(I)=FLOAT(H(I))/PC
            P(I)=100.*P(I)
            XH=XL+XINC
            WRITE(6,6)I,XL,XH,NCHARS(I),H(I),P(I)
            XL=XH
          5 CONTINUE
          6 FORMAT(13X,I2,11X,F8.3,' - ',F8.3,13X,A1,14X,I5,12X,F8.2)
            RETURN
            END

END OF COMPILATION ******
```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,

```
      SUBROUTINE CONVOL(GRID,FILTER,NR,NC,NF,L)
      REALFILTER(50,50),GRID(212,170),CON(170)
      REWIND L
      NA=NC-NF+1
      ND=NR-NF+1
      NB=1+NF/2
      DO2I=1,ND
      II=I+NB-1
      DO3J=1,NA
      JJ=J+NB-1
      SUM=0.
      DO4K=1,NF
      KK1=II-NB+K
      DO4K1=1,NF
      KK=JJ-NB+K1
      SUM=SUM+FILTER(K,K1)*GRID(KK1,KK)
    4 CONTINUE
    3 CON(J)=SUM
    2 WRITE(L,102)(CON(KK),KK=1,NA)
      ENDFILE L
      BACKSPACE L
      REWIND L
      RETURN
  102 FORMAT(160F8.3)
      END
```

* END OF COMPILATION ******

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
0002          SUBROUTINE CARDIN(MAP,NR,NC,LU,T)
0003          INTEGERIN(170)
0004          INTEGER T(2,20)
0005          REALMAP(212,170)
0006          READ(LU,13,END=99)NR,NC
0007          READ(LU,14,END=99)T
0008          DO1I=1,NR
0009          READ(LU,10,END=99)(IN(J),J=1,NC)
0010          DO2J=1,NC
0011        2 MAP(I,J)=FLOAT(IN(J))
0012        1 CONTINUE
0013          RETURN
0014       99 CONTINUE
0015          IF(LU.NE.5)REWINDLU
0017          WRITE(6,11)LU
0018          STOP
0019       10 FORMAT(4X,10I5)
0020       11 FORMAT('1',15X,'END OF FILE ENCOUNTERED ON FORTRAN LOGICAL ',I2)
0021       12 FORMAT(A1)
0022       13 FORMAT(6X,I3,2X,I3)
0023       14 FORMAT(20A4)
0024          END
```

END OF COMPILATION ******

```
13  (23 MAY 67)                                  OS/360  FORTRAN H

    COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

               SUBROUTINE G E T M (MAP,NR,NC,LU)
               REAL MAP(212,170)
               REWIND LU
               DO1I=1,NR
             1 READ(LU,10,END=99)(MAP(I,J),J=1,NC)
               REWINDLU
               RETURN
            99 CONTINUE
               WRITE(6,11)LU
               STOP
            10 FORMAT(160F8.3)
            11 FORMAT('1',15X,'END OF FILE ENCOUNTERED ON FORTRAN LOGICAL ',I2)
               END

END OF COMPILATION ******
```

```
     COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

 0002              SUBROUTINE P U T N (MAP,NR,NC,LU)
 0003              REALMAP(212,170)
 0004              REWIND LU
 0005              DO1I=1,NR
 0006              DO2 K=1,NC
 0007              IF((MAP(I,K).LT.1000.).AND.(MAP(I,K).GT.-1000.))GOTO 2
DETECTED - SCAN POINTER =      1
 0009              WRITE(6,11)I,K
 0010              MAP(I,K)=0.
 0011            2 CONTINUE
 0012           11 FORMAT(5X,'OVERFLOW AT I= ',I3,' JJ= ',I3)
 0013            1 WRITE(LU,10)(MAP(I,J),J=1,NC)
 0014              ENDFILE LU
 0015              BACKSPACE LU
 0016              REWIND LU
 0017              RETURN
 0018           10 FORMAT(160F8.3)
 0019              END
```

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

            SUBROUTINE PUTA(MAP,NR,NC,LU)
            INTEGERMAP(212,170)
            REWIND LU
            DO1I=1,NR
          1 WRITE(LU,10)(MAP(I,J),J=1,NC)
            ENDFILE LU
            BACKSPACE LU
            REWIND LU
            RETURN
         10 FORMAT(160A1)
            END

* END OF COMPILATION ******
```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
      SUBROUTINE GETA(MAP,NR,NC,LU)
      INTEGERMAP(212,170)
      REWIND LU
      DO1I=1,NR
    1 READ(LU,10,END=99)(MAP(I,J),J=1,NC)
      REWINDLU
      RETURN
   99 CONTINUE
      WRITE(6,11)LU
      STOP
   10 FORMAT(160A1)
   11 FORMAT('1',15X,'END OF FILE ENCOUNTERED ON FORTRAN LOGICAL ',I2)
      END
```

END OF COMPILATION ******

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
      SUBROUTINE ISOPAR(MAP,NR,NC,L1,L2)
      REALMAP(212,170),V(170)
      REWIND L1
      REWIND L2
      DO 1 I=1,NR
      READ(L1,10,END=99)(MAP(I,J),J=1,NC)
      READ(L2,10,END=98)(V(J),J=1,NC)
      DO 1 J=1,NC
    1 MAP(I,J)=MAP(I,J)-V(J)
      REWINDL1
      REWINDL2
      RETURN
   98 WRITE(6,11)L2
      RETURN
   99 WRITE(6,11)L1
      RETURN
   10 FORMAT(160F8.3)
   11 FORMAT('1',15X,'END OF FILE ENCOUNTERED ON FORTRAN LOGICAL ',I2)
      END
```

END OF COMPILATION ******

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,DECK,

```
      SUBROUTINE SPREAD(MAP,NR,NC,T)
      INTEGER MAP(212,170),T(2,20)
      WRITE(6,10)T
      DO1I=1,NR
    1 WRITE(6,11)(MAP(I,J),J=1,66)
      WRITE(6,10)T
      DO2I=1,NR
    2 WRITE(6,11)(MAP(I,J),J=67,132)
      WRITE(6,10)T
      DO3I=1,NR
    3 WRITE(6,11)(MAP(I,J),J=133,NC)
      RETURN
   10 FORMAT('1',26X,20A4/27X,20A4//)
   11 FORMAT(66(1X,A1))
      END
```

END OF COMPILATION ******

Program 4

This program corrects digital map values after they have been stacked on magnetic tape and numbered. Provision has been made to delete extra values, replace wrong values and insert new values.

Input:

Format (2I1)	-	logical units
Format (80A1)	-	symbols for: end of insert cards; delete; replace; insert.
Format (1X,I10)	-	number of map card where correction is to start.
Format (80A1)	-	corrected cards. If cards are inserted series terminates with end symbol.

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,

 ISN 0002            INTEGER C(80),TA,TB,A,D,R,I
 ISN 0003            READ(5,103)TA,TB
 ISN 0004            NR=0
 ISN 0005            NW=0
 ISN 0006            READ(5,100)A,D,R,I
 ISN 0007          1 READ(5,101,END=999)II,N
 ISN 0008            CALL POSIT(TA,TB,N,C,NR,NW)
 ISN 0009            IF(II.EQ.D)GOTO 1
 ISN 0011            IF(II.EQ.I)GOTO 2
 ISN 0013            READ(5,100)C
 ISN 0014            WRITE(TB,100)C
 ISN 0015            NW=NW+1
 ISN 0016            GOTO 1
 ISN 0017          2 CONTINUE
 ISN 0018            NW=NW+1
 ISN 0019            WRITE(TB,102)(C(J),J=1,55),NW,(C(J),J=66,80)
 ISN 0020          3 READ(5,100,END=999)C
 ISN 0021            IF(C(1).EQ.A)GOTO 1
 ISN 0023            NW=NW+1
 ISN 0024            WRITE(TB,102)(C(J),J=1,55),NW,(C(J),J=66,80)
 ISN 0025            GOTO 3
 ISN 0026        999 CONTINUE
 ISN 0027          4 READ(TA,100,END=998)C
 ISN 0028            NW=NW+1
 ISN 0029            WRITE(TB,102)(C(J),J=1,55),NW,(C(J),J=66,80)
 ISN 0030            GOTO 4
 ISN 0031        998 CONTINUE
 ISN 0032            REWIND TA
 ISN 0033            ENDFILE TB
 ISN 0034            BACKSPACE TB
 ISN 0035            REWIND TB
 ISN 0036            STOP
 ISN 0037        100 FORMAT(80A1)
 ISN 0038        101 FORMAT(1X,A1,I10)
 ISN 0039        102 FORMAT(55A1,I10,15A1)
 ISN 0040        103 FORMAT(2I1)
 ISN 0041            END

****** END OF COMPILATION ******
```

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINECNT=59,SOURCE,EBCDIC,NOLIST,

```
ISN 0002            SUBROUTINE POSIT(TA,TB,N,C,NR,NW)
ISN 0003            INTEGER TA,TB,C(80)
ISN 0004            IF(N.EQ.0)RETURN
ISN 0006          1 READ(TA,100,END=9)C
ISN 0007            NR=NR+1
ISN 0008            IF(N.EQ.NR)RETURN
ISN 0010            NW=NW+1
ISN 0011            WRITE(TB,102)(C(J),J=1,55),NW,(C(J),J=66,80)
ISN 0012            GOTO1
ISN 0013          9 CONTINUE
ISN 0014            WRITE(6,101)
ISN 0015            RETURN
ISN 0016        100 FORMAT(80A1)
ISN 0017        101 FORMAT(' EOF IN POSIT')
ISN 0018        102 FORMAT(55A1,I10,15A1)
ISN 0019            END
```

****** END OF COMPILATION ******

FIGURE 36

FILTERED STRUCTURE CONTOURS ON THE SUB-CRETACEOUS UNCONFORMITY

13 x 13 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

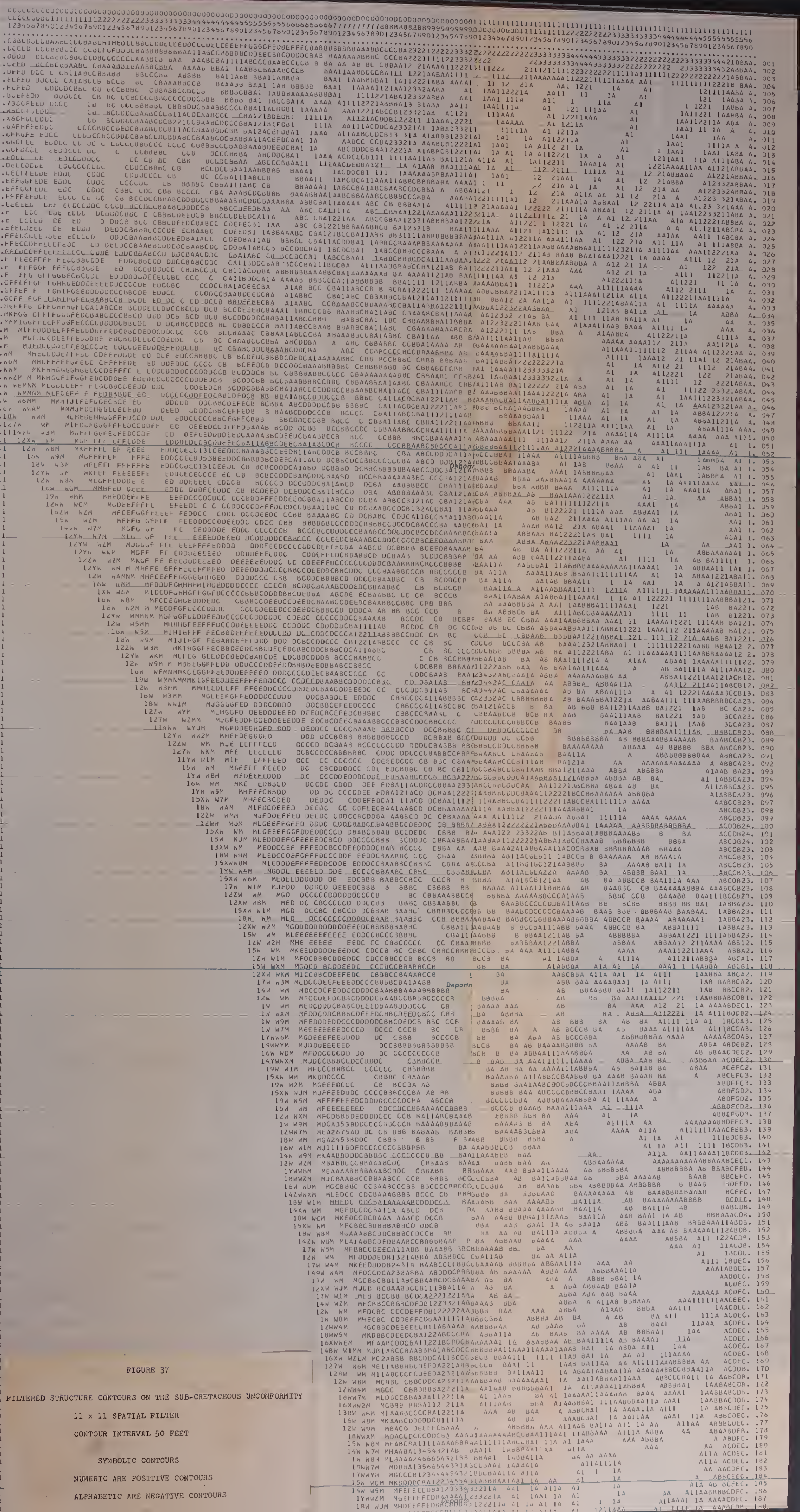

FIGURE 37

FILTERED STRUCTURE CONTOURS ON THE SUB-CRETACEOUS UNCONFORMITY

11 x 11 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

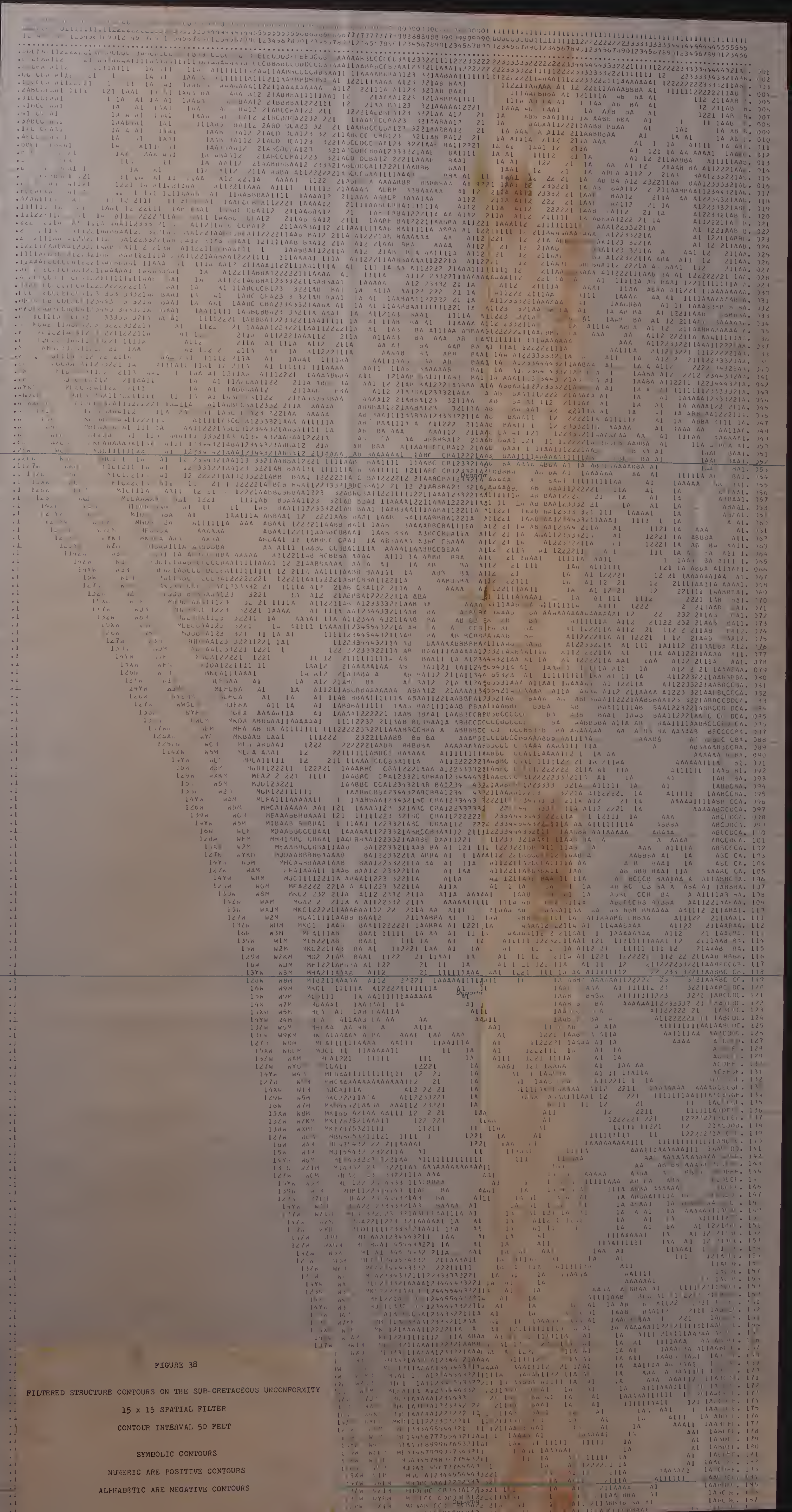

FIGURE 38

FILTERED STRUCTURE CONTOURS ON THE SUB-CRETACEOUS UNCONFORMITY

15 x 15 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

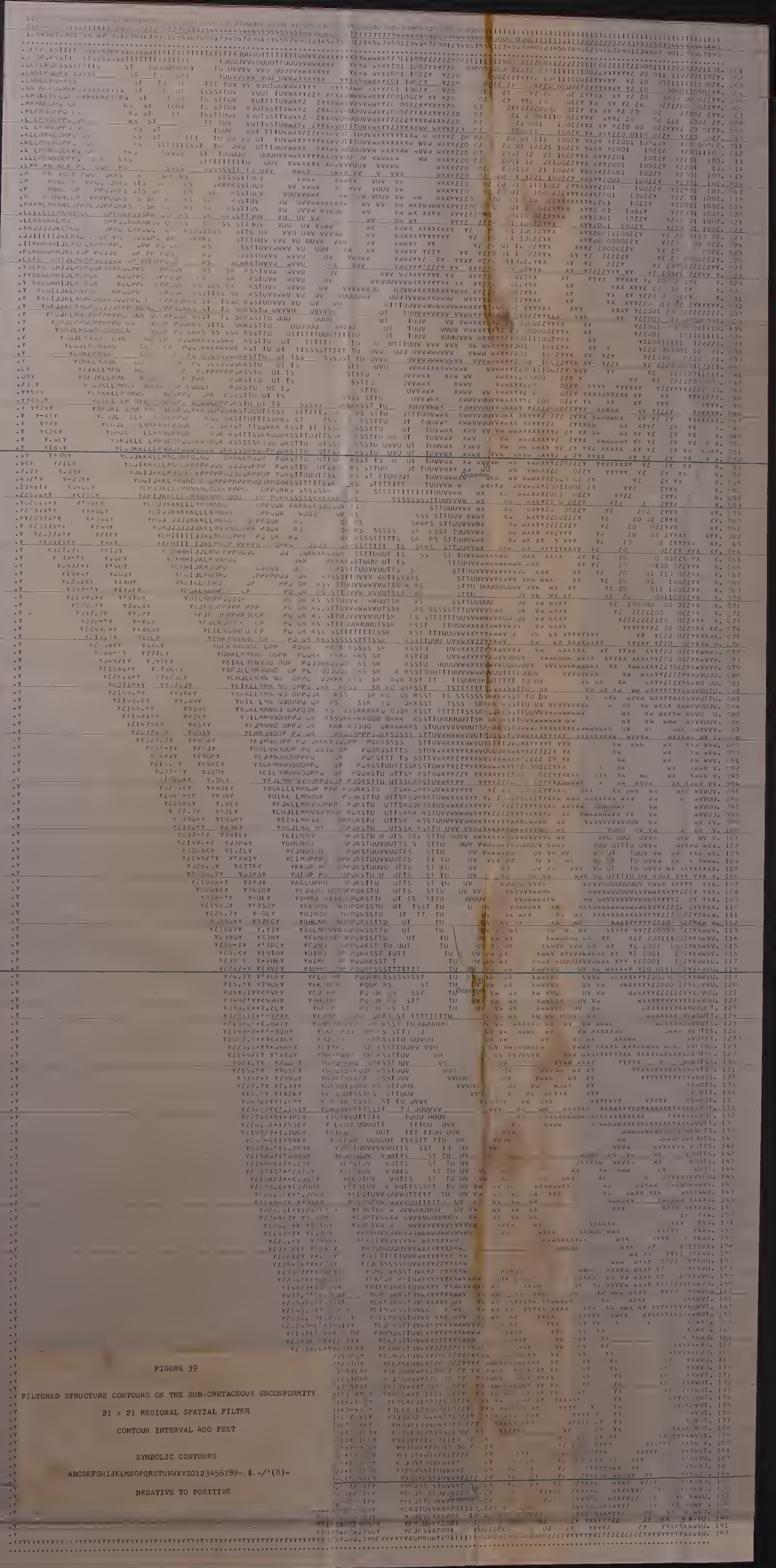

FIGURE 39

FILTERED STRUCTURE CONTOURS ON THE SUB-CRETACEOUS UNCONFORMITY

21 x 21 REGIONAL SPATIAL FILTER

CONTOUR INTERVAL 400 FEET

SYMBOLIC CONTOURS

ABCDEFGHIJKLMNOPQRSTUVWXYZ0123456789=.$.-/'(8)=

NEGATIVE TO POSITIVE

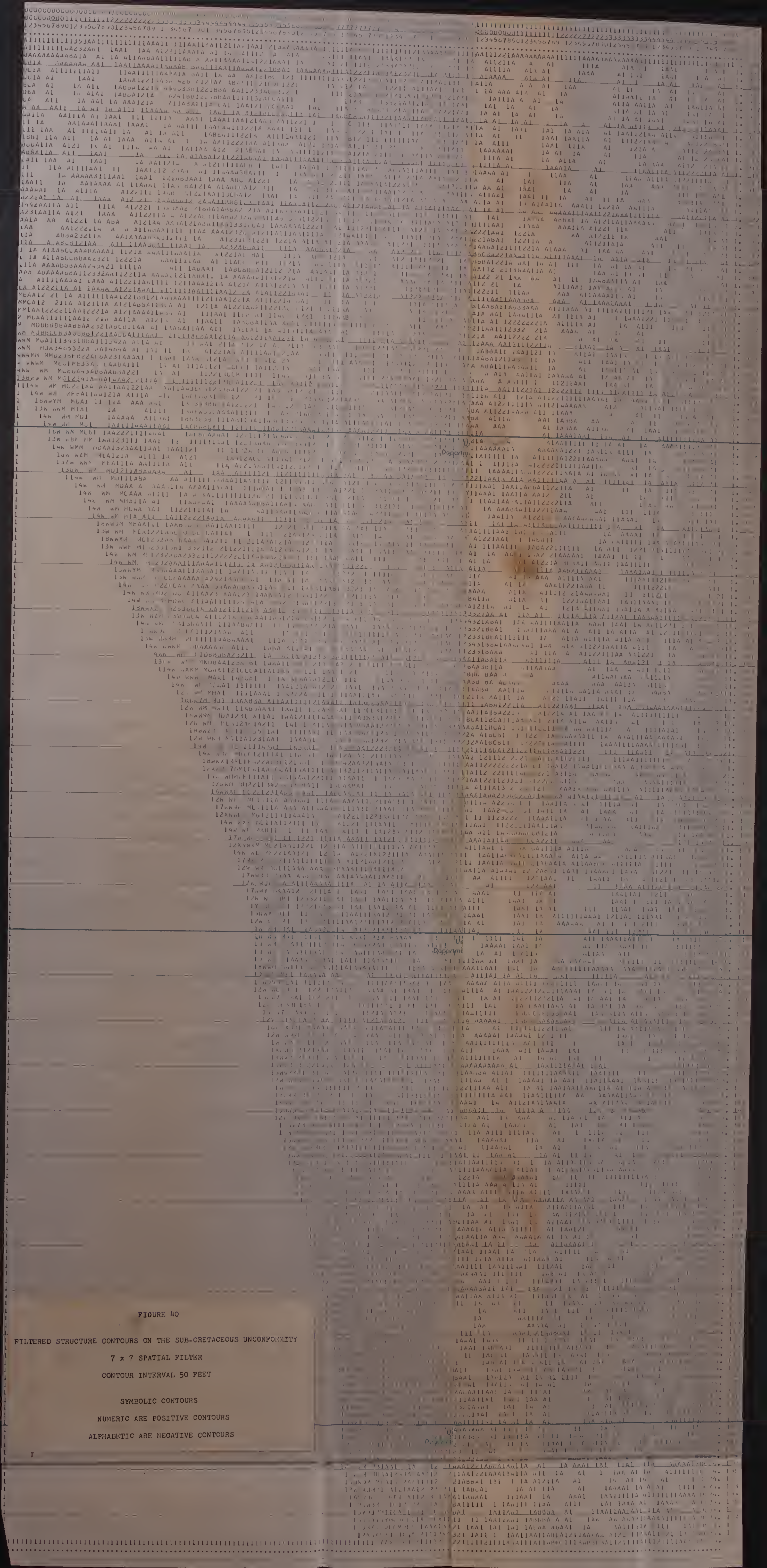

FIGURE 40

FILTERED STRUCTURE CONTOURS ON THE SUB-CRETACEOUS UNCONFORMITY

7 x 7 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

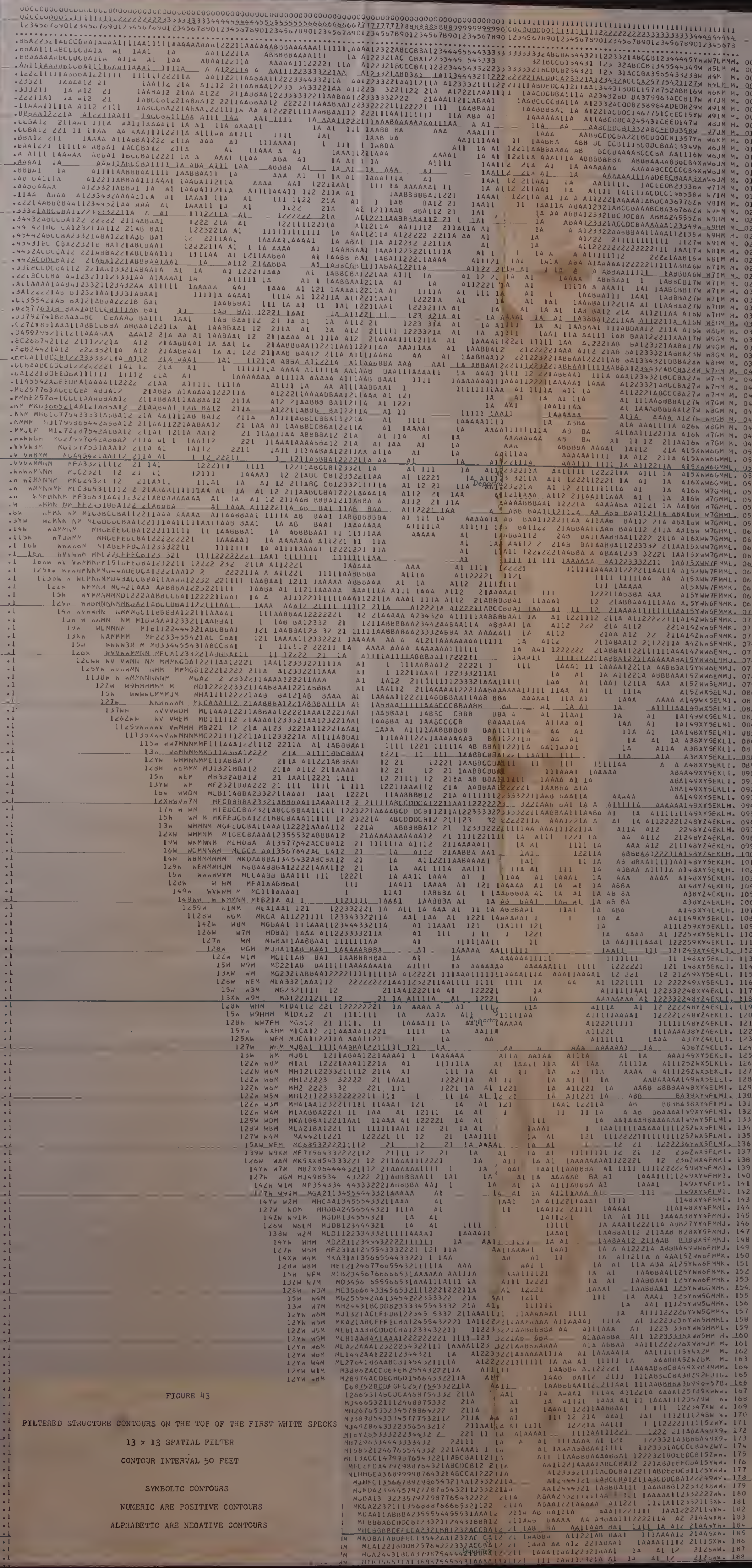

FIGURE 43

FILTERED STRUCTURE CONTOURS ON THE TOP OF THE FIRST WHITE SPECKS

13 x 13 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

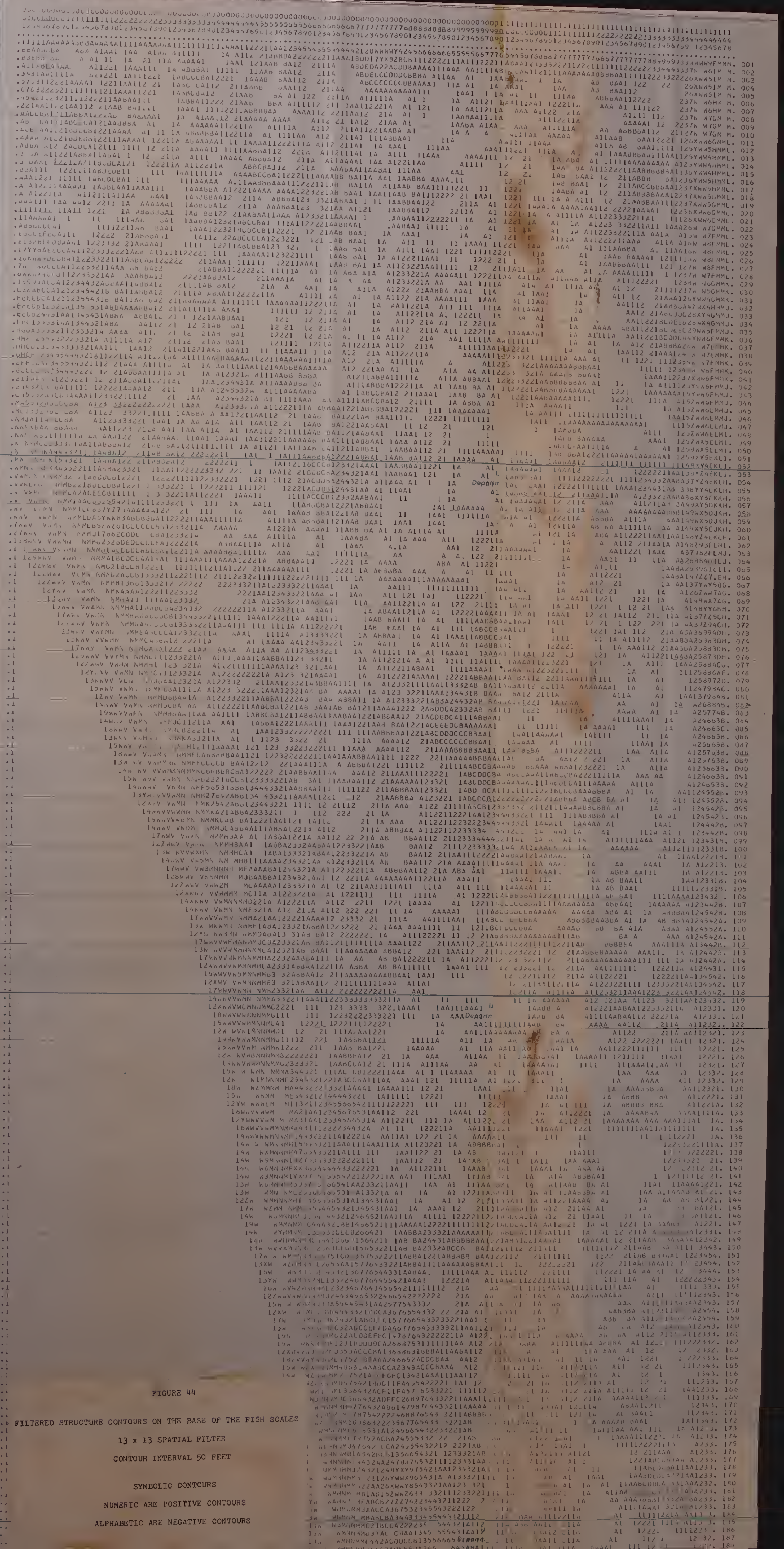

FIGURE 44

FILTERED STRUCTURE CONTOURS ON THE BASE OF THE FISH SCALES

13 x 13 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

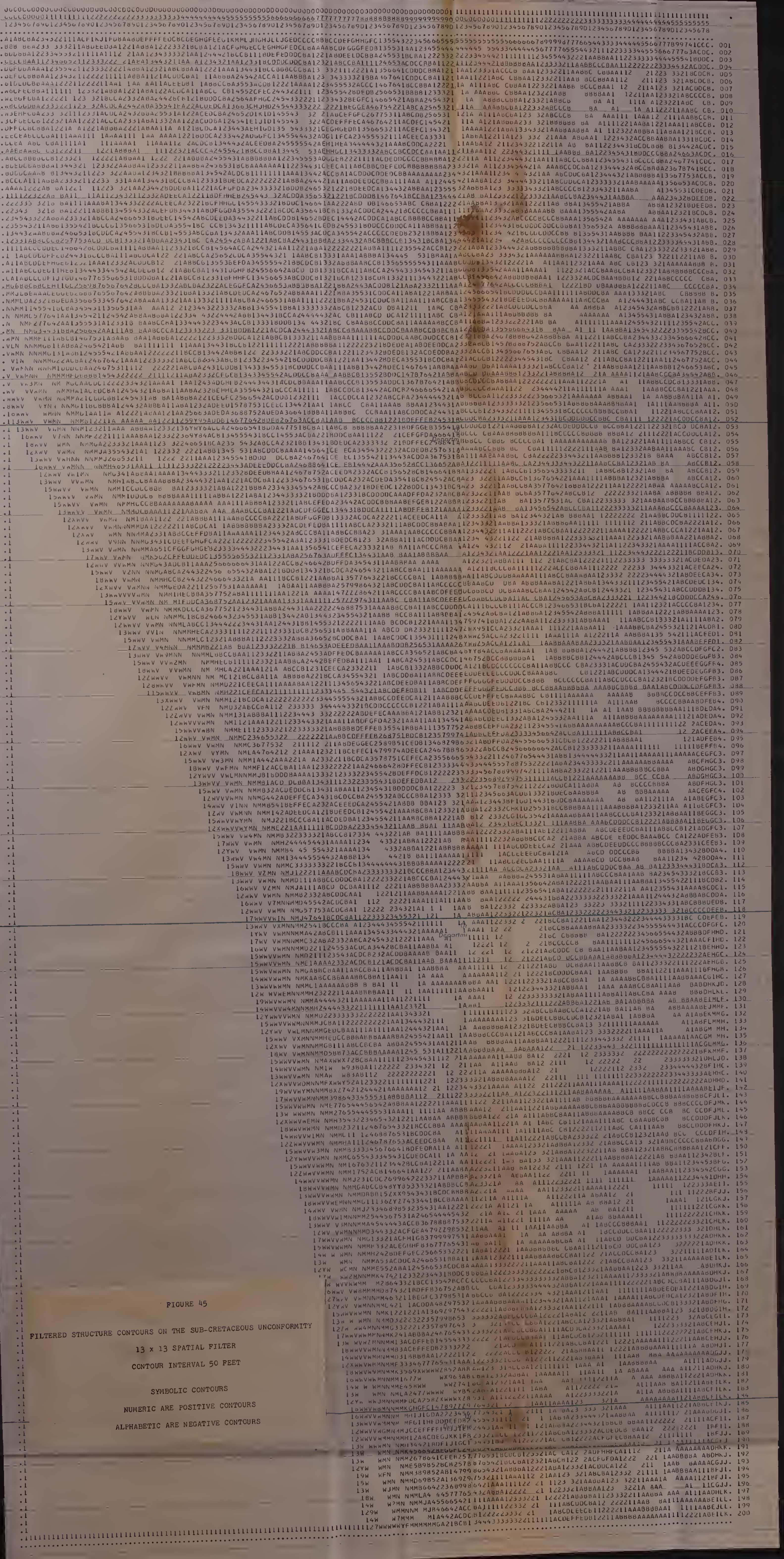

FIGURE 45

FILTERED STRUCTURE CONTOURS ON THE SUB-CRETACEOUS UNCONFORMITY

13 x 13 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

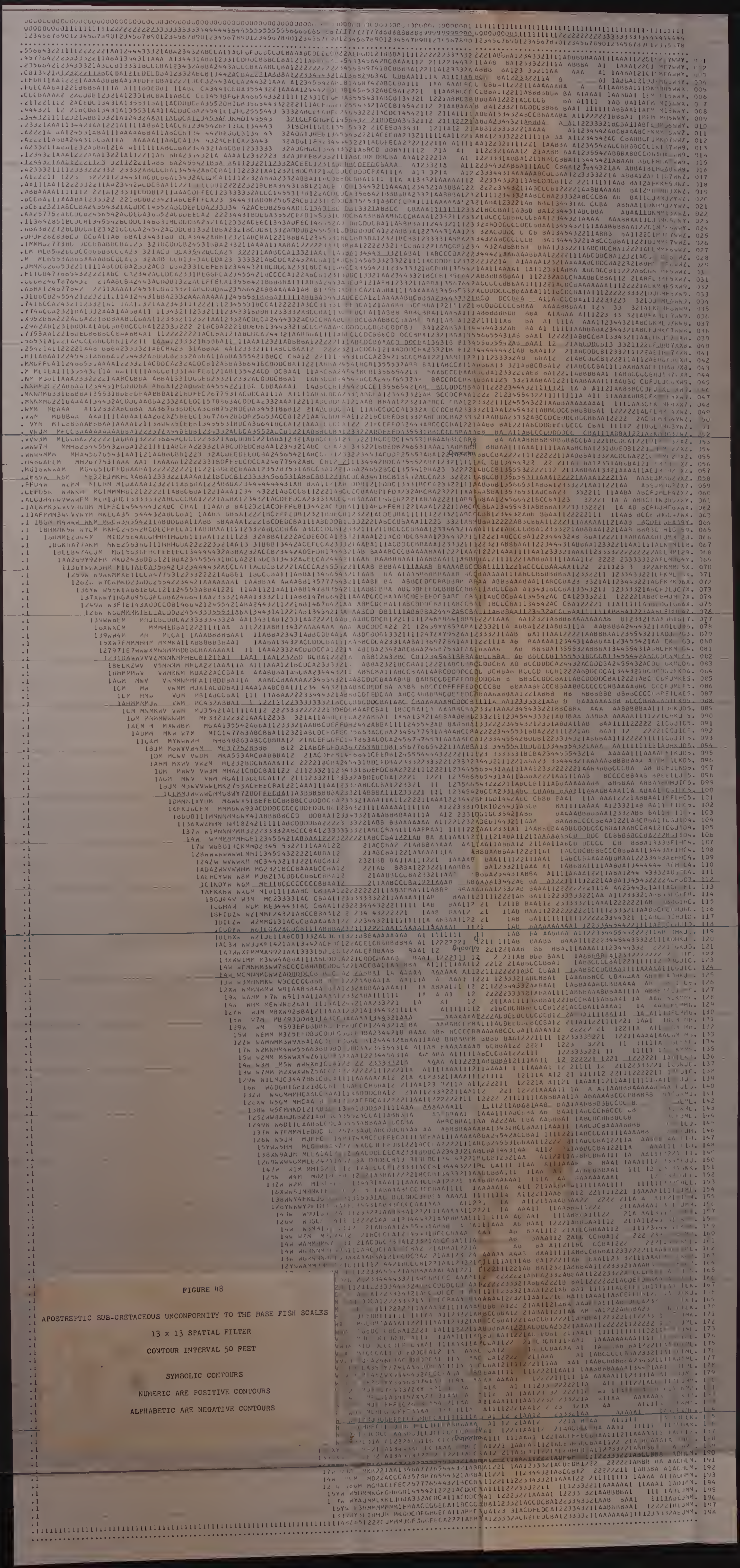

FIGURE 48

APOSTREPTIC SUB-CRETACEOUS UNCONFORMITY TO THE BASE FISH SCALES

13 x 13 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS

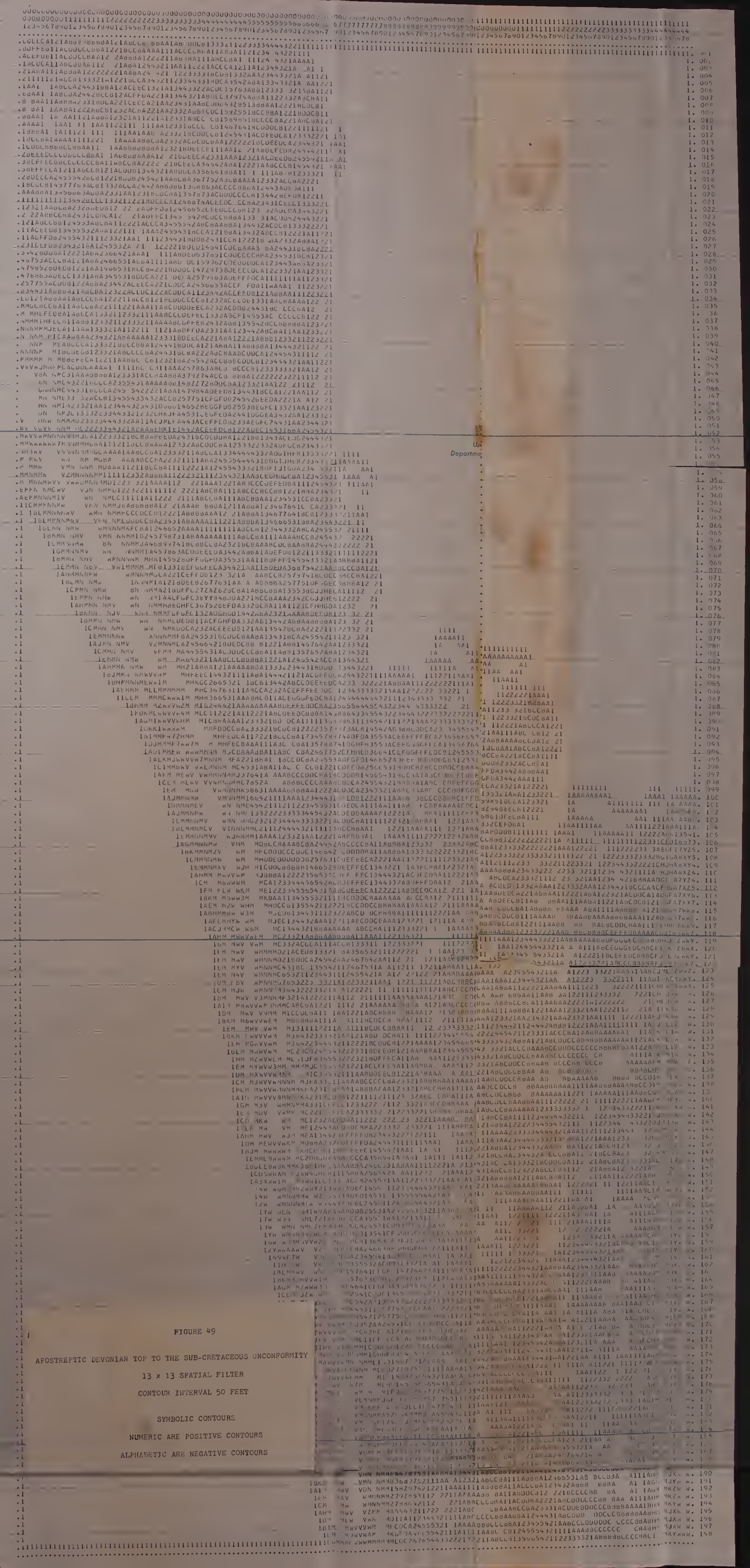

FIGURE 49

APOSTREPTIC DEVONIAN TOP TO THE SUB-CRETACEOUS UNCONFORMITY

13 x 13 SPATIAL FILTER

CONTOUR INTERVAL 50 FEET

SYMBOLIC CONTOURS

NUMERIC ARE POSITIVE CONTOURS

ALPHABETIC ARE NEGATIVE CONTOURS